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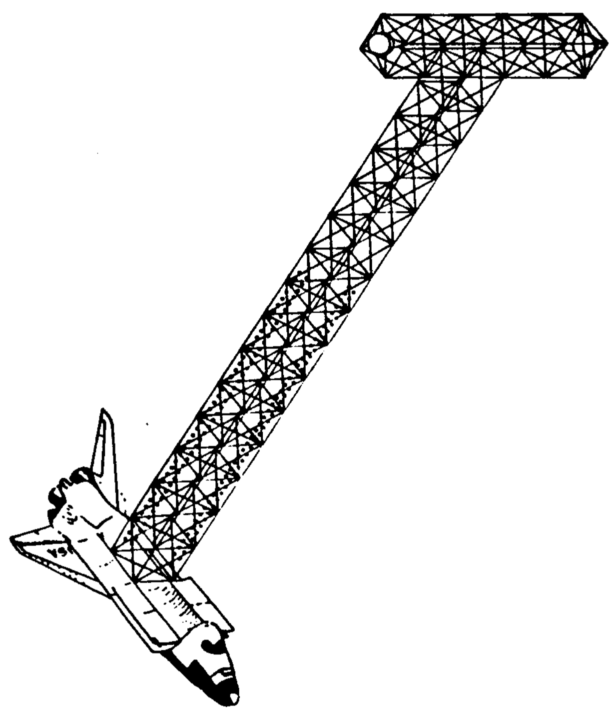
A Space Station Structures and Assembly Verification Experiment - SAVE



Richard A. Russell
J. P. Raney
L. J. DeRyder

August 1986

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

SPACE STATION STRUCTURES AND ASSEMBLY VERIFICATION EXPERIMENT - SAVE

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A SPACE STATION STRUCTURES AND ASSEMBLY VERIFICATION EXPERIMENT - SAVE

INTRODUCTION

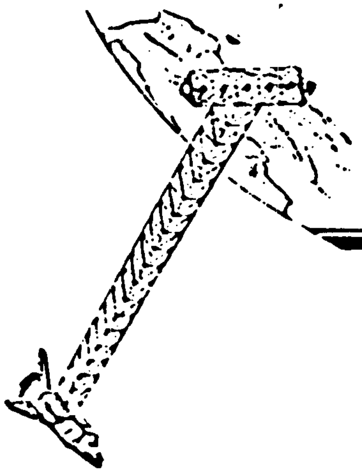
The Space Station structure has been baselined to be a 5 M (16.4 ft) erectable truss. This structure will provide the overall framework to attach laboratory modules and other systems, subsystems and utilities. The assembly of this structure represents a formidable EVA challenge. To validate this capability the Space Station Structures/Dynamics Technical Integration Panel (TIP) met on February 12 and 13, 1986 to develop the necessary data for an integrated STS structures flight experiment. As a result of this meeting, the Langley Research Center initiated a joint Langley/Boeing Aerospace Company study which supported the structures/dynamics TIP in developing the preliminary definition and design of a 5 M erectable space station truss and the resources required for a proposed flight experiment.

The purpose of the study was to: (1) Devise methods of truss assembly by astronauts; (2) define a specific test matrix for dynamic characterization; (3) identify instrumentation and data system requirements; (4) determine the power, propulsion and control requirements for the truss on-orbit for 3 years; (5) study the packaging of the experiment in the orbiter cargo bay; (6) prepare a preliminary cost estimate and schedule for the experiment; and (7) provide a list of potential follow-on experiments using the structure as a free flyer.

This report presents the results of this three month study conducted jointly by the Langley Research Center and the Boeing Aerospace Company.

EXPERIMENT OBJECTIVES

The prime objective shown on this page and the specific objectives shown on the following two pages were generated by the Space Station Structures/Dynamics TIP. It was assumed that prototype and protoflight hardware would be required to accomplish these objectives.



EXPERIMENT
PRIME OBJECTIVE

THE PRIMARY OBJECTIVE OF THE PROPOSED STRUCTURAL FLIGHT EXPERIMENT IS TO EVALUATE AND DEMONSTRATE THE VALIDITY OF THE DESIGN PROCEDURES, ANALYTICAL TOOLS, FABRICATION PROCESSES, AND GROUND TEST TECHNIQUES FOR PRODUCING A HIGH PERFORMANCE, RELIABLE PRIMARY STRUCTURE FOR THE SPACE STATION.

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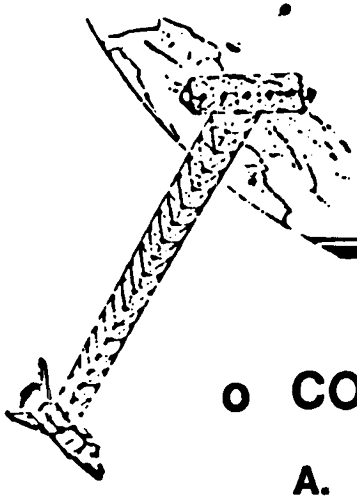

EXPERIMENT SPECIFIC OBJECTIVES

- o CONSTRUCTION TECHNIQUE OBJECTIVES

  A. ASSEMBLY TECHNIQUE VERIFICATION

  1. EVALUATE ASSEMBLY TECHNIQUES UNDER OPERATIONAL ENVIRONMENTS
  2. EVALUATE ASTRONAUT LOCAL MOBILITY/STABILITY AIDS
  3. CONCEPTS VERIFICATION
     - a. PACKAGING
     - b. ERECTION FIXTURES
     - c. ASSEMBLY PROCEDURES
     - d. LARGE STRUCTURE MATING TECHNIQUES

  B. UTILITY LINE INSTALLATION TECHNIQUE EVALUATION

  C. EVA TIMELINE VERIFICATION

  D. CREW WORKLOAD EVALUATION

  E. EVALUATION OF CREW INDUCED FORCES DURING ASSEMBLY

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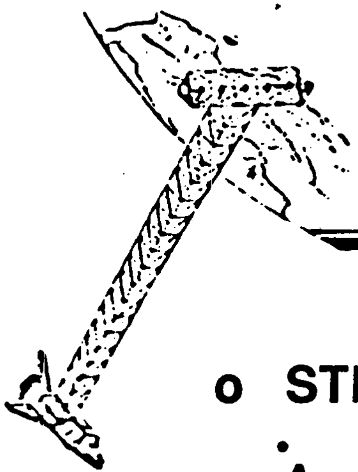


EXPERIMENT SPECIFIC OBJECTIVES
(CONT.)

- o STRUCTURAL CHARACTERIZATION OBJECTIVES

  A. BUILD PREDICTION CAPABILITY

  1. VERIFY ANALYTICAL CAPABILITY - ZERO G AND SCALE EFFECTS
  2. CALIBRATE GROUND TEST - STABILIZATION OF GROUND TEST FOUNDATION

  B. DEVELOP ON-ORBIT TEST CAPABILITY FOR UTILIZATION DURING ASSEMBLY OF THE SPACE STATION

  C. CHARACTERIZE THERMAL DEFORMATIONS AND DETERMINE "AS-BUILT" GEOMETRY IN OPERATIONAL ENVIRONMENTS

  D. DETERMINE MATERIAL ENVIRONMENTAL SUITABILITY

  E. ASSESS REPLACEABILITY OF TRUSS PARTS UNDER OPERATIONAL ENVIRONMENTS

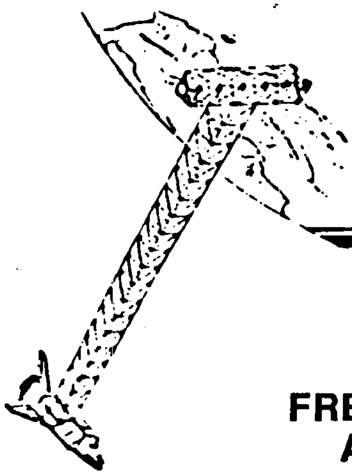
  F. ASSESS EFFECTS OF SUBSYSTEM INSTALLATIONS ON STRUCTURAL DAMPING (CABLE TRAYS, RESOURCE MODULES, ATTACHED PAYLOADS)

  G. CHARACTERIZE CREW-MOTION INDUCED FORCES

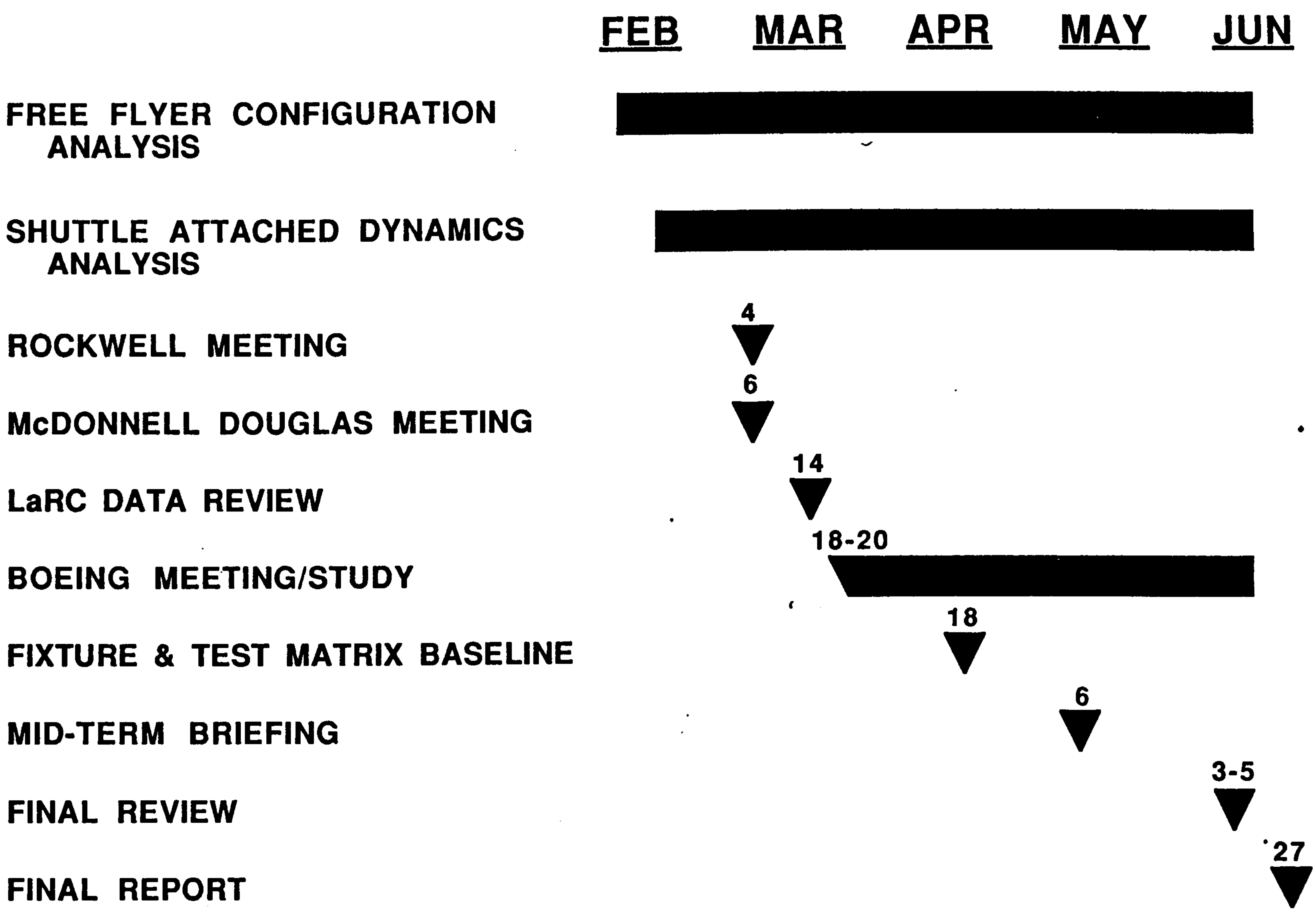
STUDY SCHEDULE

The overall study schedule is shown on this chart. Three major tasks were performed in the time frames shown on the schedule. The results of these tasks will be presented as follows:

Section I	-	Boeing Study
Section II	-	Langley Dynamic Analysis Study
Section III	-	Langley Free Flyer Analysis Study



STUDY SCHEDULE



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SECTION I

Boeing Aerospace Company Study

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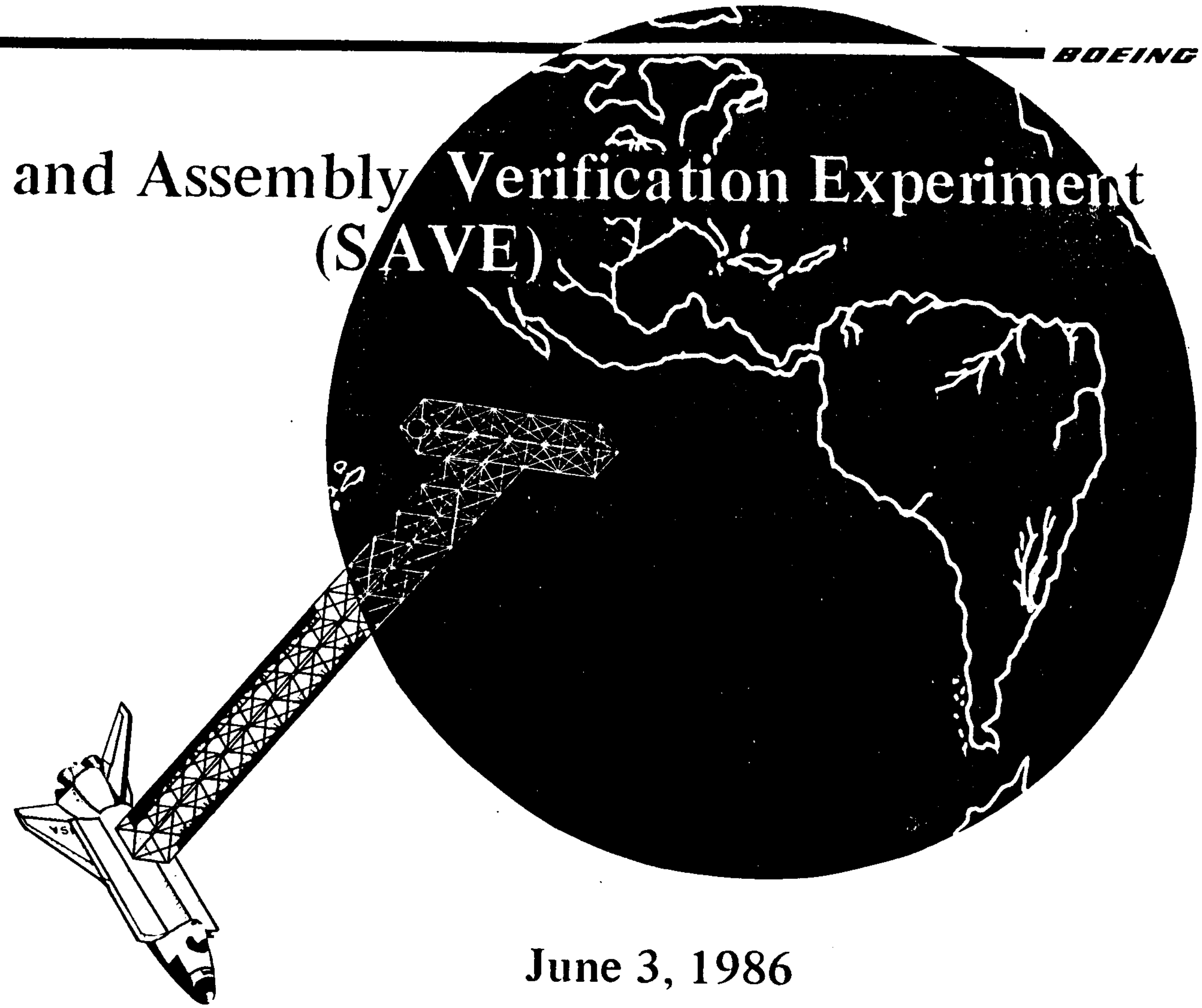
SPACE STATION

Final Review

BOEING

Structures and Assembly Verification Experiment (SAVE)



June 3, 1986

INTRODUCTION

This informal final report presents the results of a two and one-half month study conducted by Boeing Aerospace Company for NASA-Langley Research Center on Contract NAS-1-18224. The final oral review was held at Langley on June third, nineteen hundred eighty six. The Boeing work was then meshed with Langley's complementary studies and a combined Boeing/Langley team presented the results at Johnson Space Center on June fifth nineteen hundred eight six. The agenda on the facing page reflects the combined team effort.

The Boeing task was to provide support in the preliminary definition and design of a five meter erectable Space Station truss flight experiment. The purpose of the study was to: (1) Devise methods of truss assembly by astronauts; (2) define a specific test matrix for dynamic characterization; (3) identify instrumentation and data system requirements; (4) determine the power, propulsion and control requirements for the truss on-orbit for three years; (5) study the packaging of the experiment in the orbiter cargo bay; (6) prepare a preliminary cost estimate and schedule for the experiment and (7) provide a list of potential follow-on experiments using the structure as a free flyer.

Structures and Assembly Verification Experiment (SAVE)

Agenda

BOEING

8:30 a.m.	Introduction	Richard Russell
8:45	Boeing Support Activities	Don Bartlett
9:00	Study Groundrules	Dick Gates
9:15	Design Requirements	Dick Gates
9:30	Structural Dynamic Studies	Phil Raney
10:15	Experiment Design Concept	Bob Glaeser
12:00 noon	Lunch	
1:00 p.m.	Assembly Timelines	Bob Horne
1:30	Test Matrix/Test Plan	Dick Gates
2:00	Instrumentation/Data Systems	Dick Gates
2:30	Free-Flyer Requirements	Buddy DeRyder/John Coleman
3:30	Program Schedule	Don Bartlett
3:45	Program Cost Estimate	Don Bartlett
4:30	Conclusions and Recommendations	Don Bartlett/Richard Russell
5:00	Adjourn	

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PROGRAM SCHEDULE

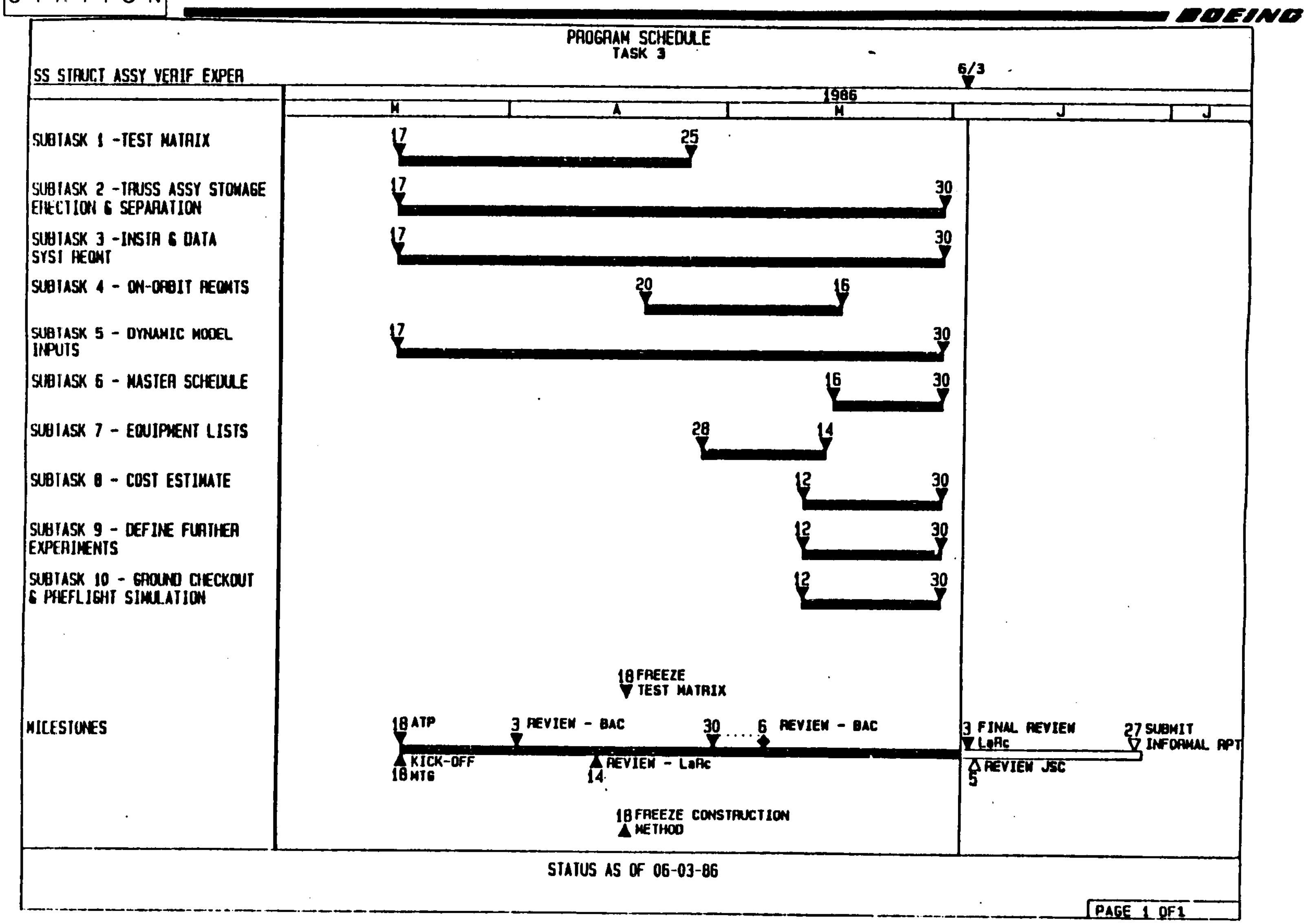
The ten subtasks of the study were performed in the time frames shown on the schedule, after a March eighteenth kickoff meeting at Langley. The major effort was in subtasks one, two and three to define the experiment assembly fixture, test matrix and instrumentation. As a part of the design development process, crew systems personnel at Boeing and Langley were instrumental in an on-going evaluation of feasibility and in determining the timelines.

The dynamic modeling activity of subtask five was performed by Langley with design data inputs supplied by Boeing. The free flyer analysis of subtask four was also performed by Langley. Definition of orbit maintenance requirements, various power bus options and costs were provided by Boeing.

The study was completed on June fifth with an oral review at Johnson Space Center. The informal report submittal followed on June twenty seventh.

Structures and Assembly Verification Experiment (SAVE)

NASA–Langley Research Center Work Pkg. A



WORK BREAKDOWN STRUCTURE

The WBS reflects all of the activities involved in an experiment of this nature. This WBS was used as an index for developing the equipment list, weight statement and cost estimate. WBS Item 1.3 Payload Equipment, was the principal area of study and costing. However, costs were estimated for engineering development tests (WBS 1.5.1) associated with the experiment specific hardware such as instrumentation and excitation systems and related software. The program schedule, shown later, is based on activity in all of the WBS items listed.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Work Breakdown Structure

BOEING

- 1.0 SAVE Flight Experiment
  - 1.1 Project Management
    - 1.1.1 Configuration Management
    - 1.1.2 Cost/Schedule Management
    - 1.1.3 Subcontractor and Supplier Management
    - 1.1.4 Shuttle Interface Management
    - 1.1.5 Safety, Reliability and Quality Assurance
    - 1.1.6 Agreement Management
    - 1.1.7 Program Management
    - 1.1.8 Program Reviews
    - 1.1.9 Transportation and Shipping
  - 1.2 System Definition and Planning
    - 1.2.1 System Definition
    - 1.2.2 Design Integrity Analysis
      - 1.2.2.1 NASTRAN Analysis
      - 1.2.2.2 IDEAS^2 Analysis
      - 1.2.2.3 Fracture Control Plan
    - 1.2.3 Safety Hazard Analysis
    - 1.2.4 Specifications
    - 1.2.5 System Test Planning
    - 1.2.6 Drawing Tree
    - 1.2.7 Materials Usage List
    - 1.2.8 Mass Properties
    - 1.2.9 Physical Flow Plan
  - 1.3 Payload Equipment
    - 1.3.1 Assembly Fixture Subsystem
      - 1.3.1.1 Assembly Fixture
      - 1.3.1.2 Astronaut Positioner System
      - 1.3.1.3 Component Stowage System
      - 1.3.1.4 Truss Lock-down Fixture
    - 1.3.2 Truss Structure Subsystem
      - 1.3.2.1 Nodes
      - 1.3.2.2 Battens, Longerons
      - 1.3.2.3 Diagonals
      - 1.3.2.4 Tip Mass
      - 1.3.2.5 Tip Mass Support Struts
    - 1.3.3 Utility Tray Subsystem
      - 1.3.3.1 Utility Trays, Power
      - 1.3.3.2 Utility Trays, Fluid
      - 1.3.3.3 Tray Support Assembly
      - 1.3.3.4 Utility Tray Stowage Containers
    - 1.3.4 Instrumentation Subsystem
      - 1.3.4.1 Static/Thermal Alignment
      - 1.3.4.2 Dynamic Response
      - 1.3.4.3 Data Recording System
      - 1.3.4.4 Cabling and Attachment Supports
    - 1.3.5 Excitation Subsystem
      - 1.3.5.1 Excitation Driver
      - 1.3.5.2 Cabling
      - 1.3.5.3 Excitation Verification Instrumentation
      - 1.3.5.4 Power Conditioning

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SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Work Breakdown Structure (Cont'd)

BOEING

1.3.6 Software
- 1.3.6.1 Assembly Fixture Control/Operation
- 1.3.6.2 Test and Data Acquisition

1.4 Ground Support Equipment (GSE)
- 1.4.1 Subsystem Assembly, Checkout and Integration
- 1.4.2 Mechanical
  - 1.4.2.1 Shipping
  - 1.4.2.2 Ground Handling Fixture

1.5 Testing and Evaluation
- 1.5.1 Engineering Development Tests
- 1.5.2 Assembly and Checkout Testing
  - 1.5.2.1 Subsystem Verification Tests
  - 1.5.2.2 Integration GSE Testing
  - 1.5.2.3 Flight Ops GSE Testing
  - 1.5.2.4 All Systems Test
- 1.5.3 Qualification Tests
  - 1.5.3.1 Static Loads
  - 1.5.3.2 Vibration and Acoustics
  - 1.5.3.3 System Outgassing/Contamination
- 1.5.4 Acceptance Tests
- 1.5.5 Operations Tests
  - 1.5.5.1 Tests in Lab
  - 1.5.5.2 Zero G Simulation Tests
- 1.5.6 Crew Training Tests
  - 1.5.6.1 Erection and Disassembly

1.6 Integration
- 1.6.1 Transportation
- 1.6.2 Payload to Orbiter
  - 1.6.2.1 Checkout Payload with GSE at KSC
  - 1.6.2.2 Deliver to OPF
  - 1.6.2.3 Mechanically Install in Orbiter
  - 1.6.2.4 Mate Data System
- 1.6.3 Flight Support GSE to POCC

1.7 Operations
- 1.7.1 Ground
- 1.7.2 Flight

1.8 Documentation
- 1.8.1 Program Management PLan
- 1.8.2 Experiment Requirements Document
- 1.8.3 Payload Accommodations Assessment
- 1.8.4 Payload Integration Plan
- 1.8.5 Safety Data Package
- 1.8.6 Interface Control Documents
- 1.8.7 KSC Activity Plan
- 1.8.8 Crew Training Manual
- 1.8.9 Flight Procedures Manual
- 1.8.10 POCC/Flight Ops GSE Interface Control Document
- 1.8.11 Tests Reports
- 1.8.12 Materials Control Document

BOEING ORGANIZATION

The Boeing team selected for the study is made up of specialists assigned to the Space Station program and from the Engineering Technology and Engineering Laboratories organizations. Technical specialists from the Inertial Upper Stage (IUS) program provided consultation and direction on orbiter integration, operational and design details.

Cost estimating support was provided by the Finance estimating organization. Scheduling support was obtained from Program Planning and Control personnel in the IUS program. A broad spectrum of skills were available to apply to specific areas of study.

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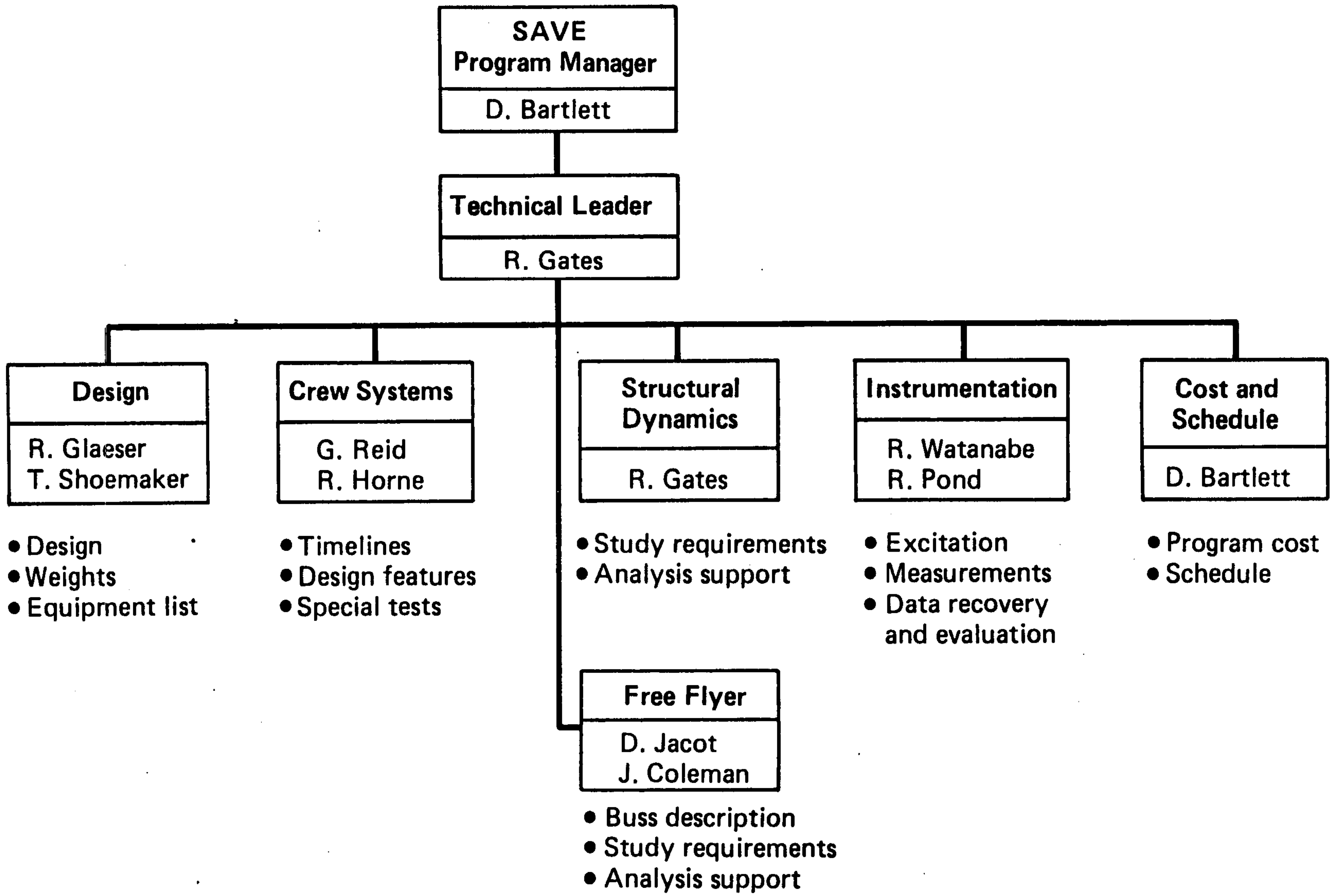
Structures and Assembly Verification Experiment (SAVE)

Boeing Team Organization



STUDY GROUNDRULES

At the outset of the study, groundrules were identified to form a starting point. These groundrules pertained to the overall experiment, truss structure, assembly fixture, utility trays and operations. During the study, as the design concepts evolved, the groundrules were modified to reflect increasing knowledge of the experiment requirements, its behavior and the requirements and capabilities of the Orbiter and EVA astronauts. Many design and operational options were explored, particularly in the areas of assembly fixture design and assembly operations. Truss structure groundrules are based on the current Space Station configuration. Utility tray groundrules are the least rigorous due to the current immaturity of the Space Station utility tray design. The groundrules listed on these two pages are the result of this evolutionary process.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Study Groundrules

BOEING

Total experiment
- Provide for instrumentation stowage and installation
- Electronics capability interface is available, eg. STEP
- Goals: 3 year lifetime on orbit
  - Use up to half of STS stowage and assembly capability
  - Total weight less than 6804 kg (15000 lbs) 250 n.m. orbit

Truss structure
- Assemble 16 bays of 5-meter space station prototype truss
- 4 bay "T" configuration with 2-453.5 Kg (1000 lb) tip masses
- Build in STS Z axis
- Use current design concepts
  - Al clad GrEp struts
  - Al nodes and joints - LaRC design
- No spare parts unless packaging volume permits
- No on-orbit subscale tests

Assembly fixture
- The assembly fixture shall:
  - be deployable/erectable
  - provide necessary DOF for truss assembly
  - provide motorized motion for truss assembly and movement
- Assembly fixture outside of truss
- Two rail with forward lock-out
- No hydraulic drive mechanisms
- Storage container location forward

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SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Study Groundrules (cont'd)

BOEING

Utility trays

- Provide for stowage and installation of utility trays
- Pre-integrated deployable/erectable trays with flexible joints*
- Two trays (one for electrical and one for fluid lines)
- Non load carrying structure
- Internally mounted on two opposite sides of truss (on the astronaut working sides)
- Deployable/erectable
- Attach to lower 8 bays
- Hard attach to nodes at first bay and subsequent discrete points, soft attach at each 5-meter bay

Operations

- Limit power requirements to STS payload allowable value
- Construction technique will be EVA friendly
- Mechanical translation of astronauts as baseline
- Attach utilities and instrumentation during truss assembly
- Free flyer: minimum requirements to maintain orbit

*Mating the joints between utility tray segments, although not a part of this study, could influence EVA timelines significantly.

DESIGN REQUIREMENTS

In addition to the groundrules, specific requirements were identified for the design of the experiment. To be representative of the Space Station, the fundamental truss bending frequency must be approximately one-half Hertz and its torsional frequency below one Hertz. During construction, the experiment should exhibit a fundamental frequency above three-tenths Hertz to prevent detrimental interaction with the Orbiter Digital Autopilot (DAP). The assembly fixture must allow the truss to be rigidly attached to the Orbiter longerons for dynamic testing. The interface stiffness must be sufficient so that the attachment method does not significantly affect the primary frequencies of the truss. Primary RCS thruster firings are not permitted unless the truss is rigidly attached to the Orbiter longerons, and then only in combinations that do not result in loads that exceed the truss structural capability (including a factor of safety). Thus the truss and the assembly fixture must be individually capable of withstanding these contingency PRCS loads. The packaged experiment must withstand the launch and emergency landing load environments. To provide for emergency return to Earth, the experiment must be capable of being jettisoned at any time during the mission by two independent means, and the combination must be two fault tolerant. Utility tray parameters, although not firmly established by the Space Station program, were established as representative of Space Station to provide a firm basis for system weight, cost and operational scenarios. This experiment is limited to two six-hour EVA periods (twenty-four manhours) although additional EVA periods may be possible (up to thirty-six or forty-eight manhours).

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Design Requirements

BOEING

Truss structure
- –Exhibit a torsional frequency less than 1 Hz
- –Truss/Orbiter stiffness criteria
  - –Construction: f >.3 Hz
  - –Test: maintain lowest truss frequencies
- –Primary truss loads due to test excitation and PRCS firing shall be passed through the structure to the Orbiter sills without going through the assembly fixture*

Assembly fixture
- –Must withstand launch loads in the stowed configuration
- –Must withstand primary thrust loads in the deployed configuration
- –Accommodate rigid attachment of the truss to the STS sills for dynamic testing

Utility trays
- –2.5 meter length baseline (consider 5 meter length)
- –Cross section dimensions and weights:
  - Fluid-102 x 762 mm (4" x 30"): 10.4 kg/m (7 lb/ft) total
  - Electrical-102 x 1016 mm (4" x 40"): 18.1 kg/m (12.2 lb/ft) total

Operations
- –Capable of being remotely jettisoned (2 indep., 2 fault tolerant)
- –EVA reqmts limited to 2 astronauts for two 6-hr EVA periods

* PRCS firing is on contingency basis only. Loads due to PRCS firing must be limited to less than the experiment structural capability, including a factor of safety.

BASELINE DESIGN DESCRIPTION

The experiment payload equipment (Section 1.3 of the Work Breakdown Structure) includes the assembly fixture, truss structure, utility trays, instrumentation, excitation subsystem, and associated software. Design descriptions of the major components of each, with the exception of software, are given in the following charts. Software is required to deploy and restow the assembly fixture (if it is automated), control the astronaut positioning system, control the truss translation mechanism, and control and monitor the truss tests.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Baseline Design Description

BOEING

1.3.1 Assembly Fixture Subsystem
- Assy Fixture
- Astronaut Positioning System
- Component Stowage System
- Truss Lock-down Fixture

1.3.2 Truss Structure Subsystem
- Nodes
- Battens
- Longerons
- Diagonals
- Tip Mass
- Tip Mass Support Structure

1.3.3 Utility Tray Subsystem
- Utility Trays, Electrical
- Utility Trays, Fluid
- Utility Tray Support Assys
- Utility Tray Stowage Canisters

1.3.4 Instrumentation Subsystem

1.3.5 Excitation Subsystem

1.3.6 Software

DESIGN EVOLUTION

The next two charts show the evolution of the SAVE design. During periodic reviews, design and groundrule decisions were made to narrow the options down to a single baseline design concept.

At the beginning of the study, several different assembly fixture concepts were postulated:

1. Assembly fixture crossmounted to the Orbiter centerline and attached to both longerons.

2. Assembly fixture sidemounted, with the assembly fixture oriented parallel to the Orbiter centerline.

3. Component storage canisters and the astronaut positioning system centrally located within the truss structure, with the truss supported either internally or externally.

4. Two rail assembly fixture supporting the truss at opposite corners.

The cross mounted assembly fixture emerged as the baseline design concept.

The number of truss bays required was initially set at twenty plus a four bay "T". Further analyses showed that the frequency requirements could be met using a sixteen bay truss with a four bay "T". This reduced the experiment weight, stowage volume, and timelines.

Both internal and external truss drive mechanisms were considered. The external drive mechanism was selected based on lessons learned in studies of the MRMS drive system.

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Structures and Assembly Verification Experiment (SAVE)

Design Evolution

BOEING

April 3 (BAC)	April 17 (LaRC)	May 6 (BAC)	June 3 (LaRC)
Assembly Fixture			
• Crossmounted to ℄ • Sidemount to ℄ Truss Symmetrical Truss Unsymmetrical • Central Core Ext Assy Fixture Int Assy Fixture • Opposed Kingpost Truss Rotated Truss Unrotated	• Crossmounted → 2 Rail Assy Fixture • Sidemounted Truss Symmetrical	→	→
Truss Structure			
• 20 Bays High	20 Bays High Locked Rigidly to Orb. →	16 Bays High → →	→ →
Truss Translation			
• External Drive • Internal Drive	→	→	→

DESIGN EVOLUTION (cont'd)

Two astronaut positioning arm concepts were considered along with a positioning system attached to the central stowage canister concept and an articulating arm system mounted to an Orbiter bay pallet and extending to the outside of the truss. The design evolved to the "L" arm concept.

A trade study was conducted to determine whether two or four truss component canisters are required. The results of the trade study (discussed in more detail in a subsequent chart) showed that two stowage canisters are preferred.

The size of the utility trays, their configuration and installation method were topics that received much attention but were difficult to define. Until the Space Station utility tray design matures, a representative configuration (two and one-half meter foldable trays) was established as a groundrule. Utility tray design will be a significant design driver for the assembly fixture, stowage pallets, operational procedures, timelines and attachment methods. The number and position of utility trays for the experiment was determined through a trade study to be discussed in a subsequent chart.

Structures and Assembly Verification Experiment (SAVE)

Design Evolution

BOEING

April 3 (BAC)	April 17 (LaRC)	May 6 (BAC)	June 3 (LaRC)
Astro. Positioning			
• "J" Arm →			
• Internal Circular	Internal Scissor	"L" Arm →	
Component Stowage			
• 2 Canisters →	→	Trade Study →	
• 4 Canisters →	→		
Utility Trays			
• 5 Meter Length	2½ Meter Length →	→	
• 10 Meter Length	Foldable		
• One Side-All Way	One Side-All Way		
• Two Sides-½ Way	Two Sides-½ Way →	→	

BASELINE DESIGN DESCRIPTION

This figure shows the completed SAVE truss configuration, i.e. a sixteen bay truss with a four bay "T", with utility trays attached to opposite faces of the bottom eight bays. Also shown is a close-up of the assembly fixture arrangement.

The assembly fixture consists of a frame structure supported from a pallet structure by a system of braces which allow the frame to rotate to a horizontal position for launch. This pallet along with a second pallet are attached to the Orbiter through standard trunnion fittings and keel pins and also serve to support the utility tray containers and the tip masses. The truss guide rails, the astronaut positioning system and the truss translation mechanism are all supported by the assembly fixture frame. During truss assembly, the previously completed truss bay is attached to the assembly fixture at six points: two on the truss translation mechanism, two on the upper end of the truss guide rail, and two at the upper end of the truss stowage canisters. The truss component stowage canisters are attached to the forward pallet and are interconnected by tubular cross-braces. Also shown in the figure are optional canister braces which may be required to provide fore-and-aft support. Further analysis will be required to determine the need for these braces.

SAVE
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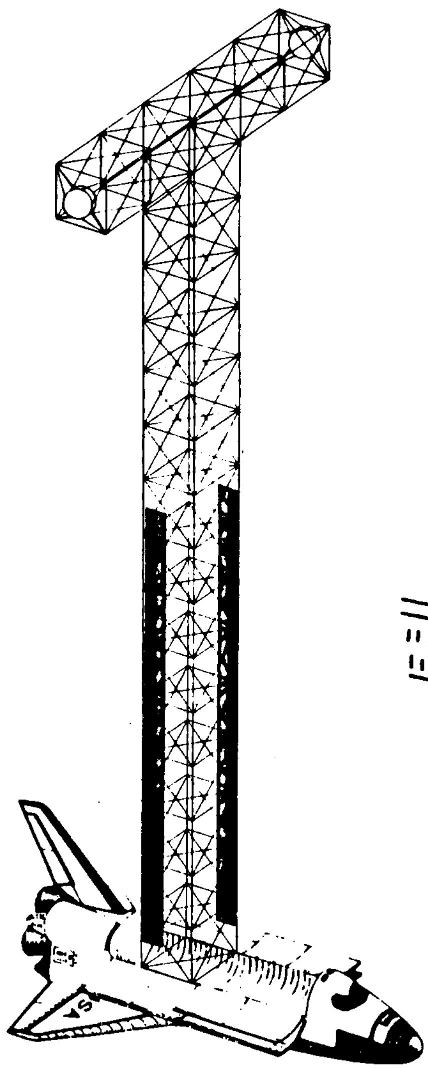
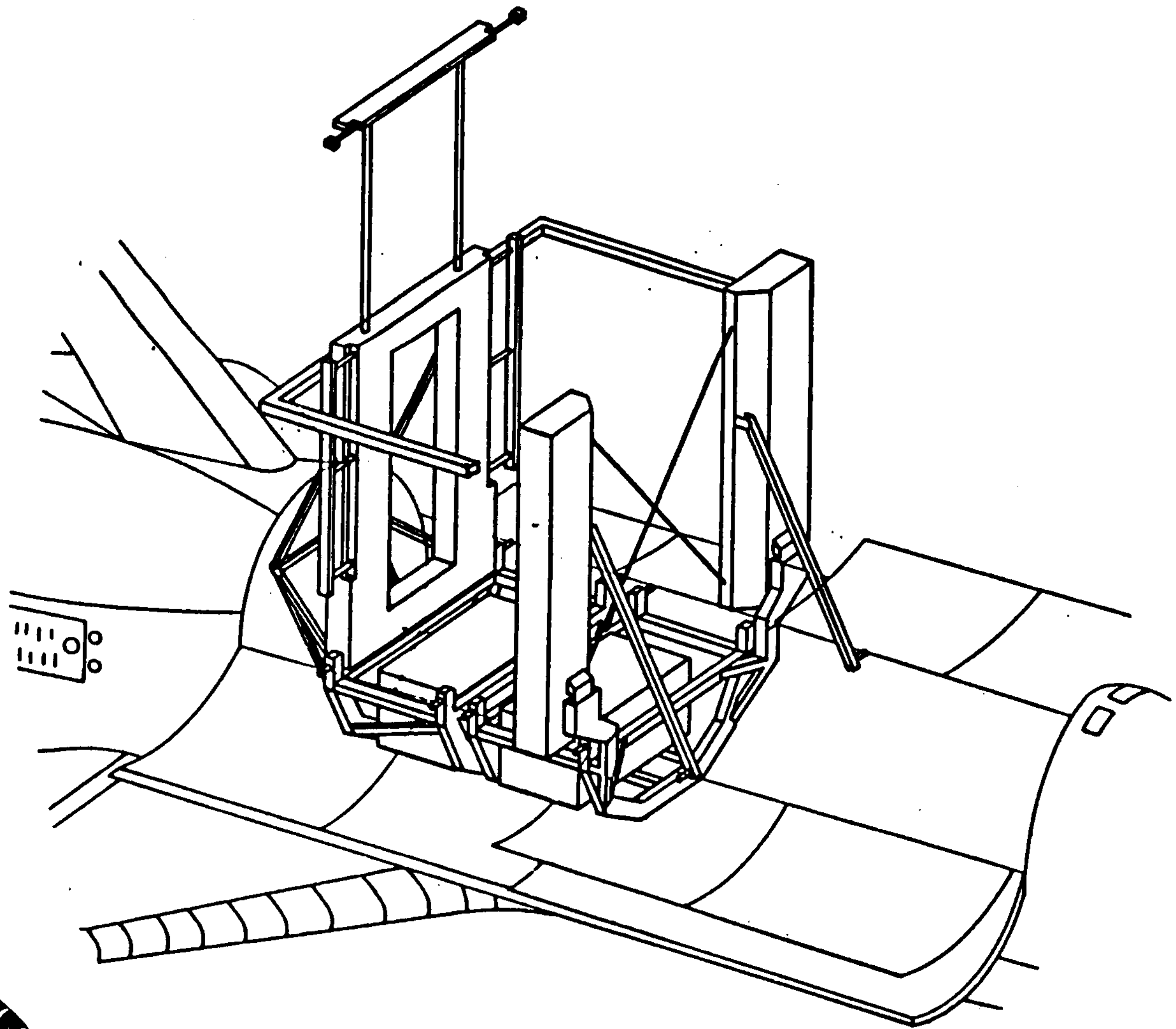
Structures and Assembly Verification Experiment (SAVE)

Baseline Design Description





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EXPERIMENT PACKAGING ARRANGEMENT

The experiment is packaged within one-half of the Orbiter payload bay length. The pallet support structure, utility trays, Orbiter hard mounts and the tip masses are located in the lower half of the circular cross section, while the assembly fixture, astronaut positioning system and truss component stowage canisters are located in the upper half.

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SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Design Concepts

BOEING

Stowed arrangement in payload bay
- Lower half
  - Pallet support structure
  - Utility trays
  - Orbiter hard mounts
  - Tip mass
- Upper half
  - Assembly fixture including diagonal supports
  - Astronaut positioning system
  - Truss component stowage canisters

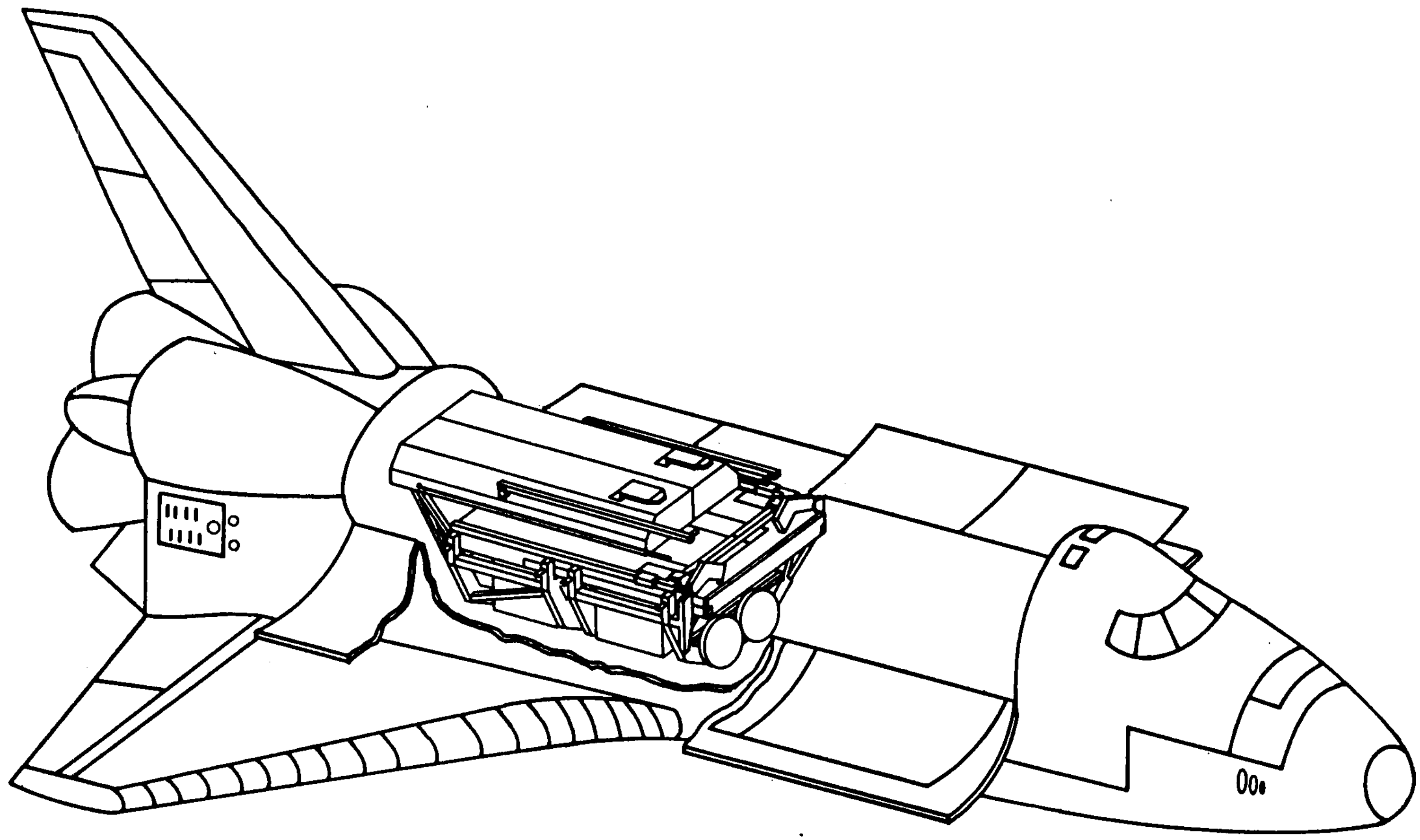
STOWED EXPERIMENT

The experiment is stowed with the assembly fixture rotated and locked in a horizontal position with the truss guide rails and translation mechanism retracted. The astronaut positioning arms are retracted and rotated so they are parallel to the assembly fixture frame. The truss member stowage canisters and their braces are attached to the back of the assembly fixture frame. The tip masses are attached to the forward face of the forward utility tray pallet.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)
Assembly Sequence

BOEING



ERECTABLE STRUT ATTACHMENT METHOD

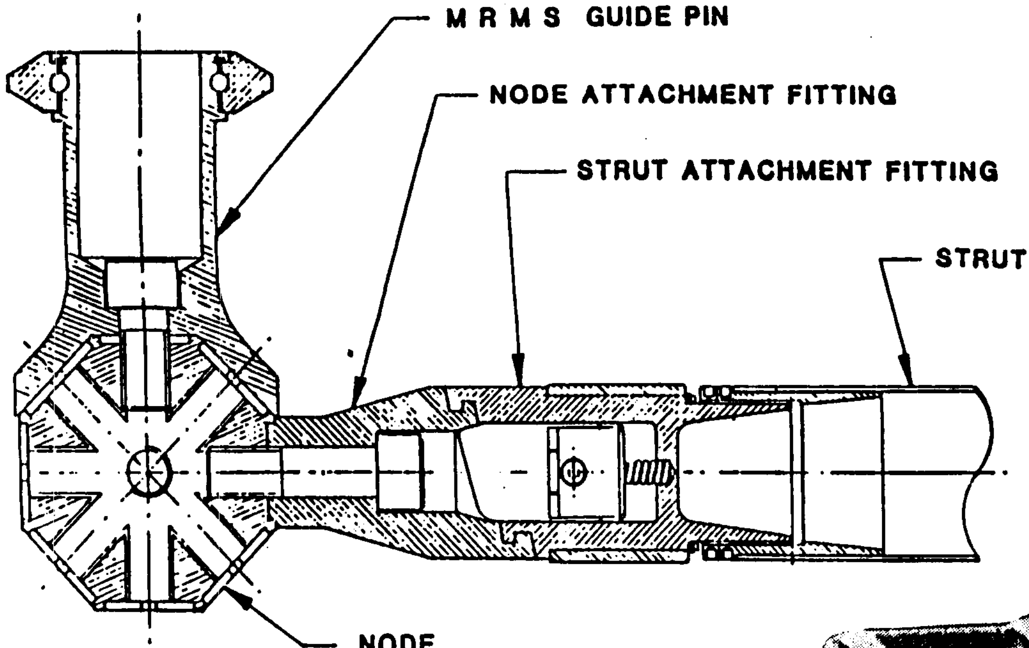
The Space Station truss identified in the groundrules is a five-meter, assemblable truss whose struts are fifty-one mm (two in.) diameter graphite/epoxy tubes with aluminum coating for atomic oxygen protection. The truss nodes are the NASA/LaRC quick connect joints shown in the figure. The node is a machined ninety-four mm (approx. four inch) diameter aluminum ball with twenty six tapped holes for node attachment fittings. The joints are manually assemblable with a self-latching feature that allows one-handed assembly and latching. A rotating collar on the strut attachment fitting compresses internal springs that apply a preload to the joint and provides a positive lock.

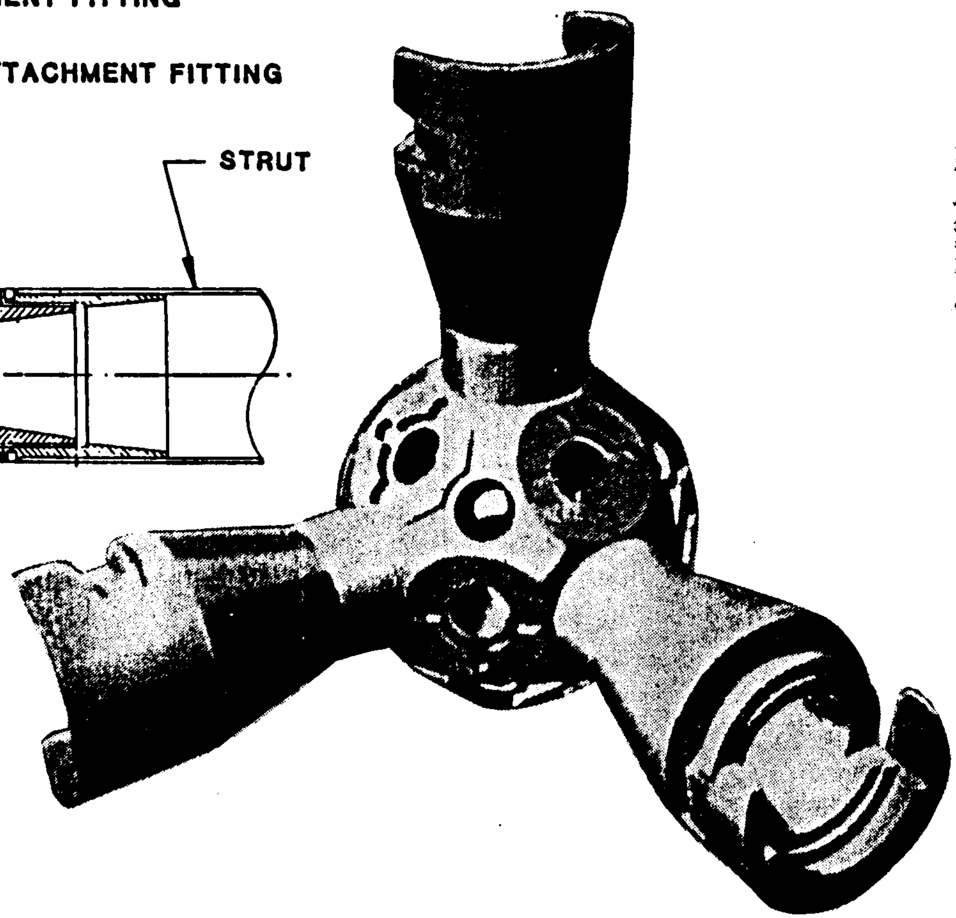
SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Erectable Strut Attachment Method

BOEING





BASELINE DESIGN DESCRIPTION

The next two charts show the utility tray mounting structure and attachment scenario.

The figure on the left shows the utility tray mounting structure installed within the truss bay. It is a tubular frame structure constructed in a manner similar to the truss and attached to the truss nodes at the "payload attachment" locations. Parallel vertical members spaced to accommodate the utility tray width are used for rigid attachment of the trays. The utility trays are shown as they unfold from their stowage containers within the cargo bay. Although they are shown attached to the outboard face of the attachment structure, they can be attached to either the outboard face or the inboard face.

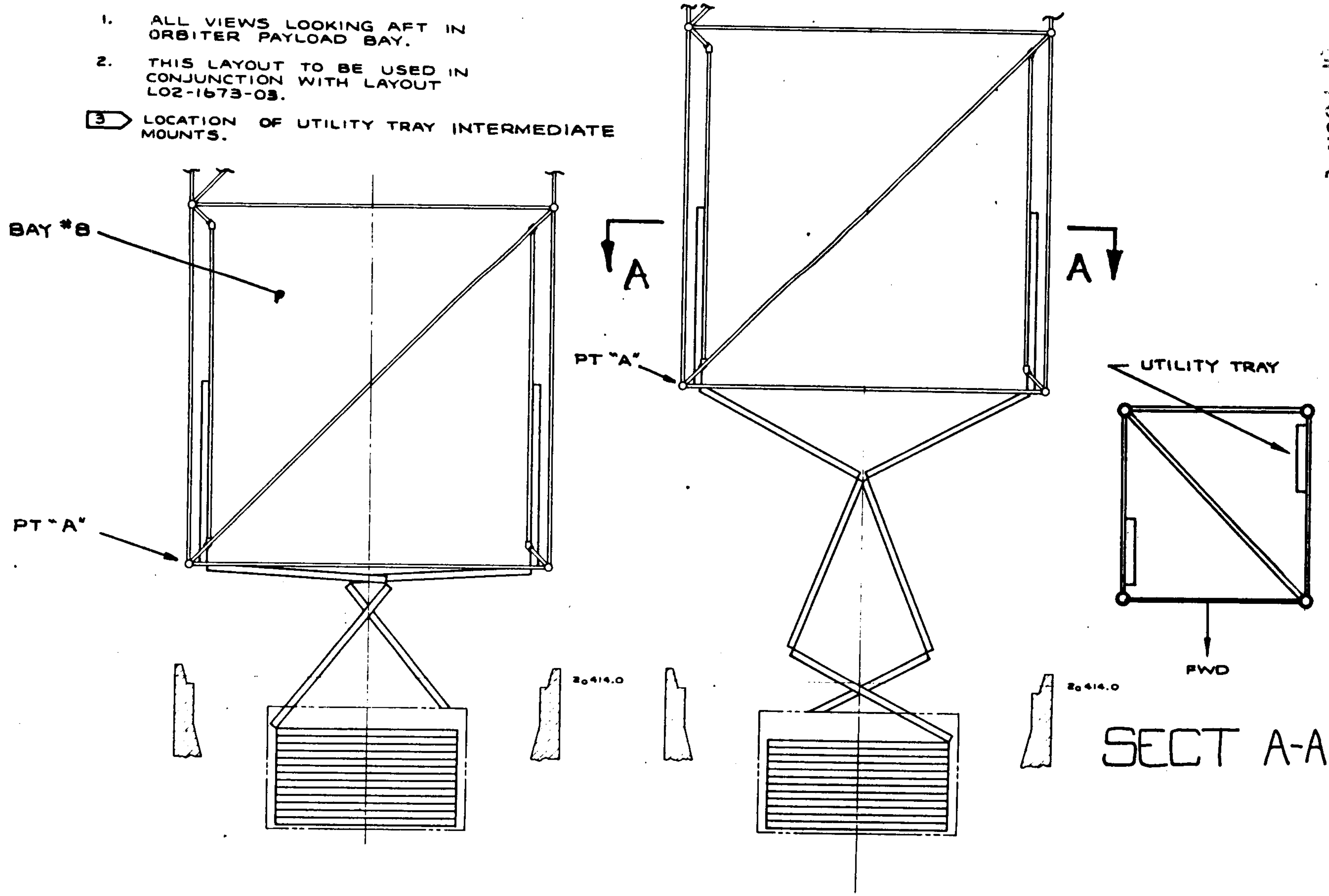
The right-hand figure shows the truss translated two and one-half meters upward to show how the trays unfold. It may be necessary to translate the truss to this position to initiate tray installation in order to allow room for the astronauts to retrieve the first section of utility trays. Once the astronaut has obtained the free end of the utility tray, the astronaut positioning system can be used to translate both the astronaut and the utility tray to the truss for attachment.

Structures and Assembly Verification Experiment (SAVE)

Baseline Design Description

NOTES:

1. ALL VIEWS LOOKING AFT IN ORBITER PAYLOAD BAY.
2. THIS LAYOUT TO BE USED IN CONJUNCTION WITH LAYOUT L02-1673-03.
3. LOCATION OF UTILITY TRAY INTERMEDIATE MOUNTS.



BASELINE DESIGN DESCRIPTION

The figure on the left shows the truss translated another two and one-half meters upward and a new truss bay assembled below it. The utility trays follow along and are attached to soft mounting structure attached to the truss node.

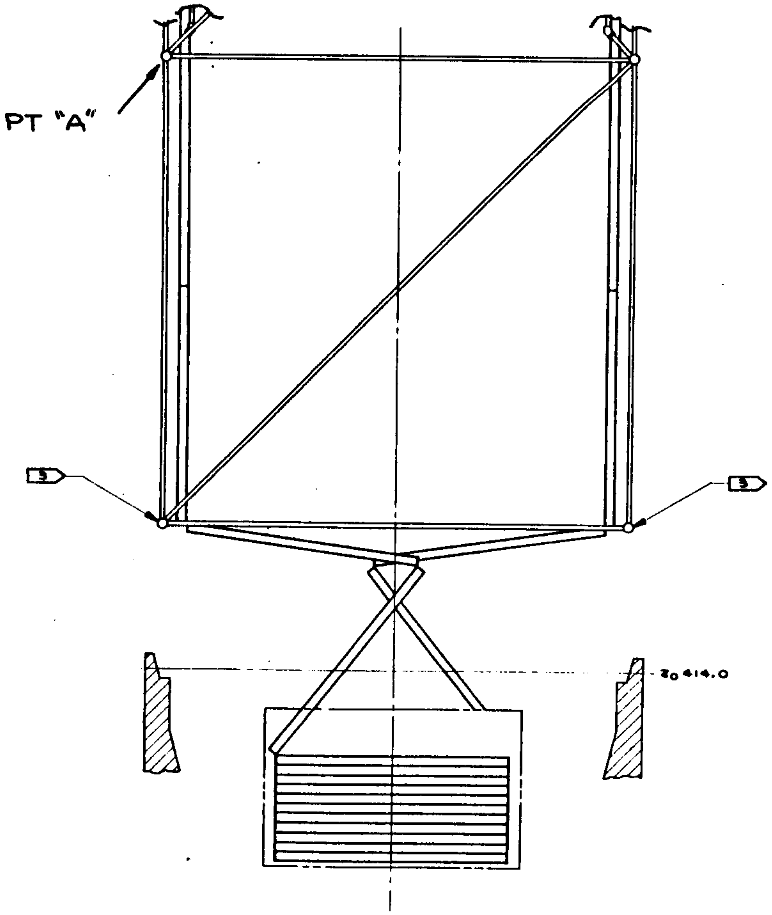
Structures and Assembly Verification Experiment (SAVE)

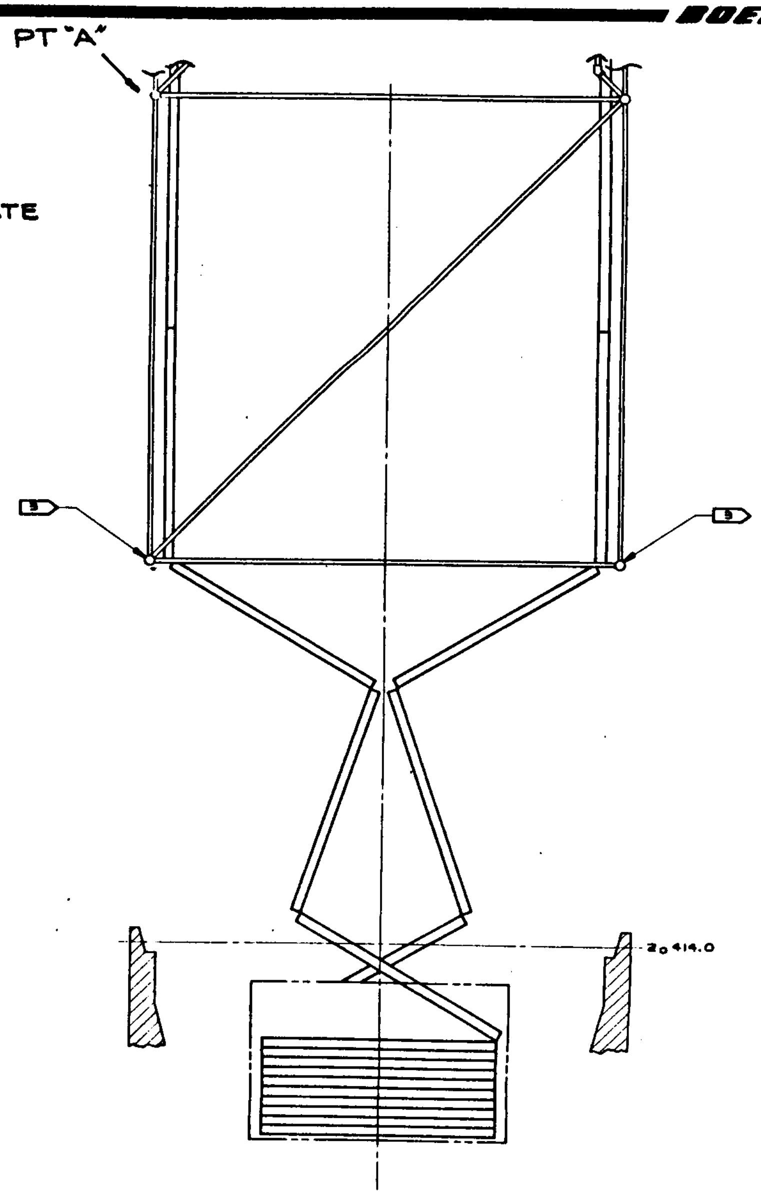
Baseline Design Description

NOTES:

1. ALL VIEWS LOOKING AFT IN ORBITER PAYLOAD BAY.
2. THIS LAYOUT TO BE USED IN CONJUNCTION WITH LAYOUT L02-1673-03.

3 LOCATION OF UTILITY TRAY INTERMEDIATE MOUNTS.





TRADES - COMPONENT STOWAGE CANISTERS

A trade study was conducted to determine the number and location of truss component stowage canisters. Two options were investigated: two canisters located at the forward corners of the truss, and four canisters, one at each corner of the truss. Design implications (quantity, complexity, weight, stowage volume, and part count) were determined along with operational effects such as set-up procedures and timelines. The most significant factor that influenced the choice of the two canister design was the lack of sufficient stowage volume for four canisters. The next two charts show the strut and node arrangements within the canisters for the two options.

SAVE
0073

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Trades-Component Stowage Canisters

BOEING

Study Item	2 Canisters	4 Canisters
1. Structural Attachment Quantity and Complexity	2 Forward Attachments	2 AFT Attachments & 2 Forward Attachments
2. Weight	1176 lbs / 533 kg	1807 lbs / 819 kg
3. Canister Stowage	Stowed Above Assembly Fixture	Stowage Volume Not Available
4. Part Count	30 Parts	46 Parts
5. Canister Installation Procedure	Installed by RMS and EVA	Additional AFT Canister Parking, Translation, Set-up
6. EVA Timeline	Truss Assembly Time 34 Minutes Greater Than 4 Canister Concept	Greater Assembly Fixture Set-up Time Than 2 Canister Concept

SELECTED CONCEPT

STARBOARD CANISTER (2 CANISTER CONCEPT)

The cross section dimensions of each truss component canister are shown on the figure. The canisters are seven meters (two hundred eighty inches) long. The starboard canister contains forty diagonals, forty-three battens, forty longerons and forty-two nodes. There is additional volume for utility tray and tip mass attachment struts and other hardware. Since the battens and longerons are shorter than the diagonals, there is room below them for storage of nodes. The port stowage canister is a mirror image of the starboard canister and contains sixty-one diagonals, forty-one battens, forty longerons and forty-two nodes.

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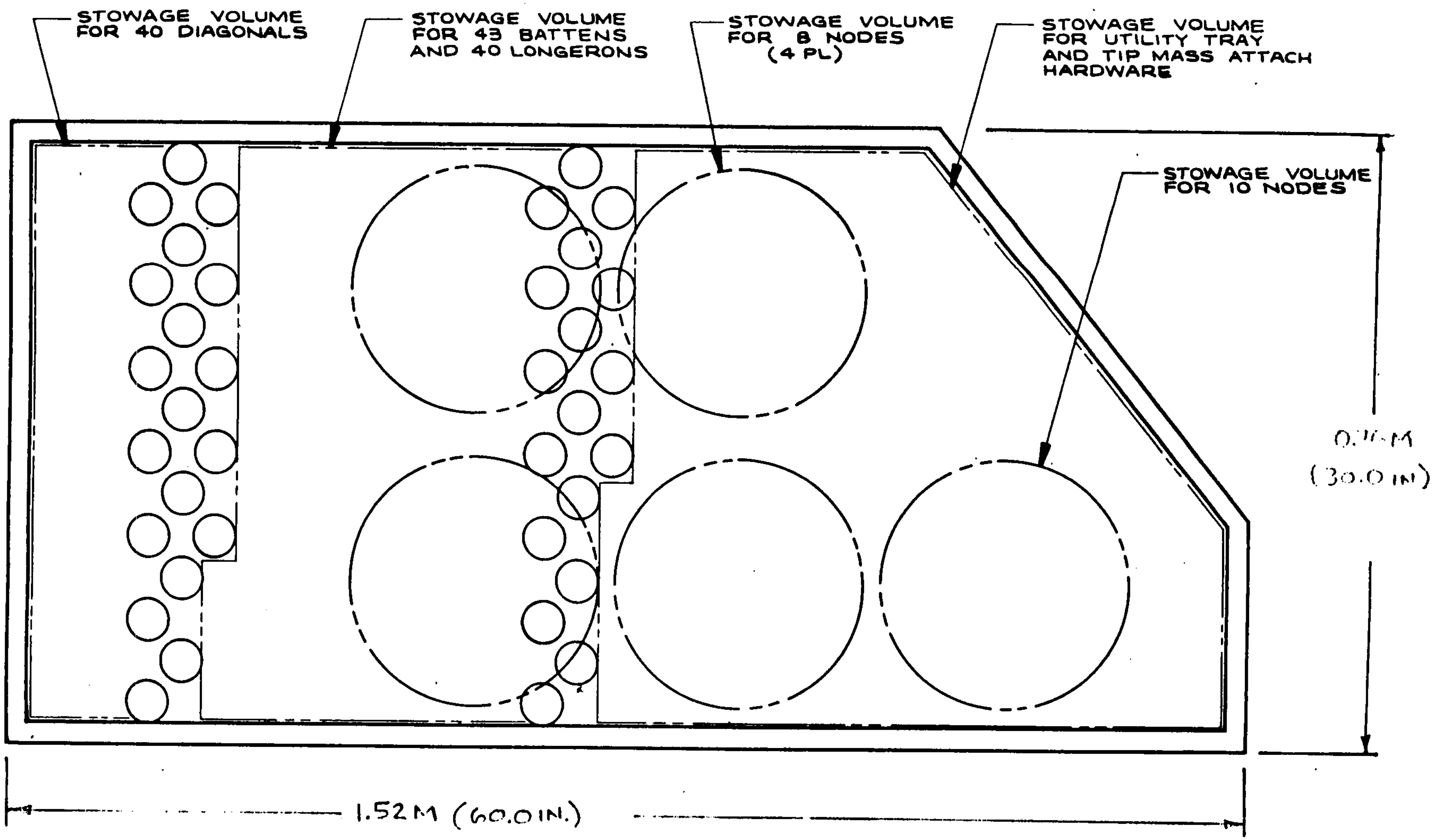
Structures and Assembly Verification Experiment (SAVE)

Starboard Canister (2 Canister Concept)



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CANISTER ARRANGEMENT (4 CANISTER CONCEPT)

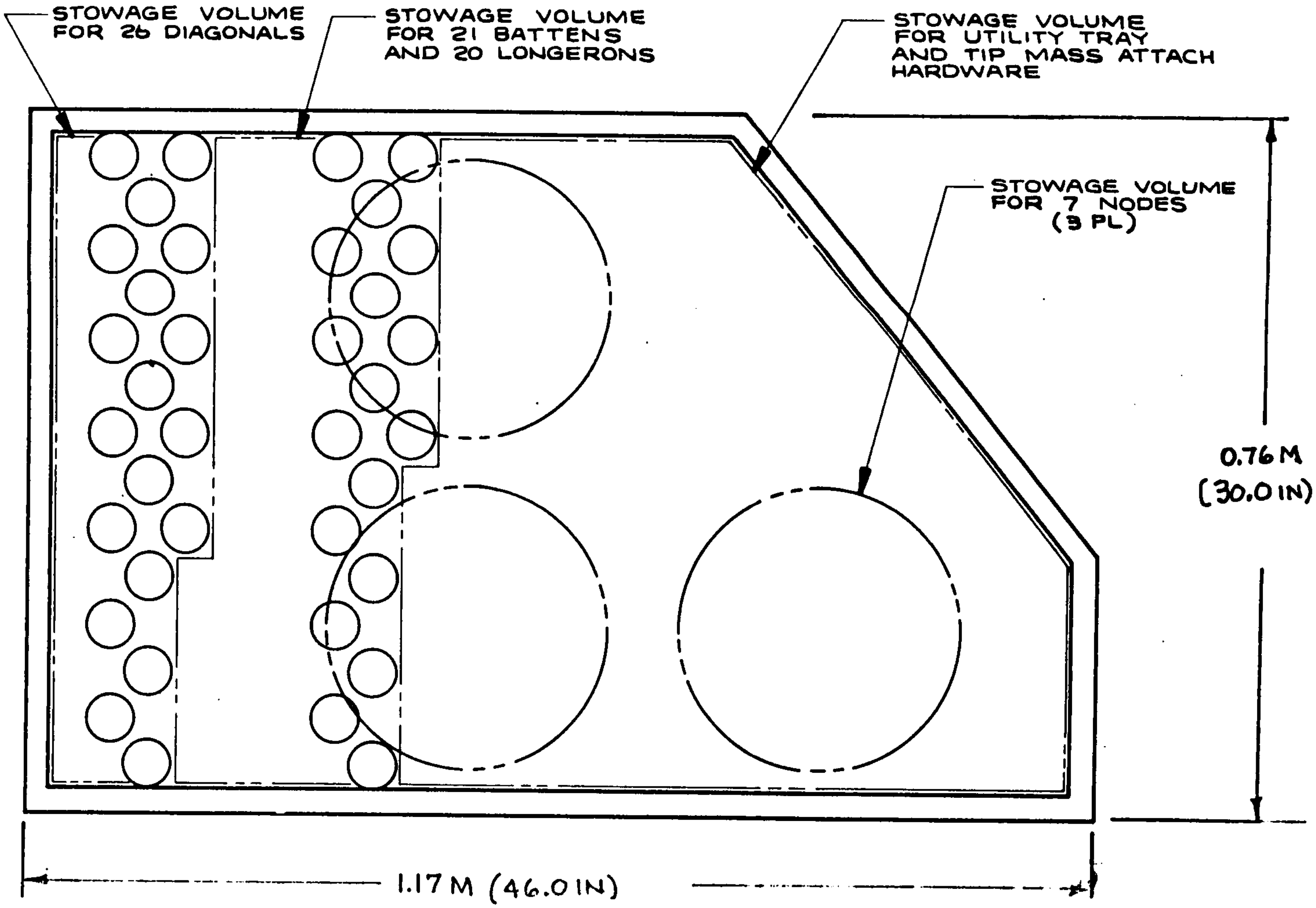
The overall dimensions of each of the four truss component canisters are shown on the figure. The canisters are seven meters (two-hundred eighty inches) long. The truss elements are divided equally between the canisters, with the exception of the diagonals.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Canister Arrangement (4 Canister Concept)

BOEING



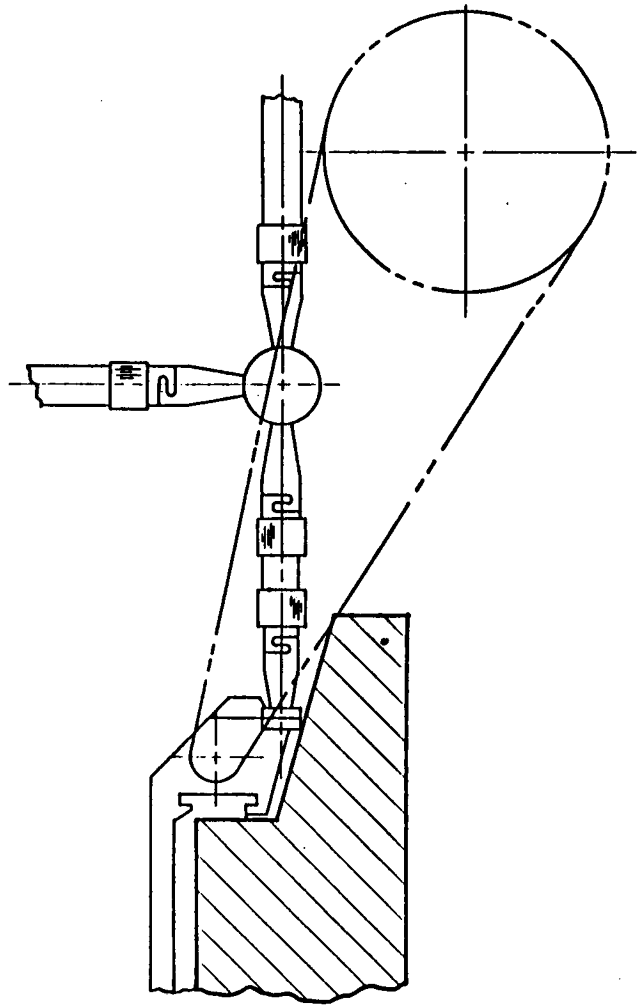
SILL FITTING

At the end of each EVA period, the truss will be rigidly mounted to the Orbiter longerons to provide the desired boundary conditions for the dynamic tests. The attachment method shown in the figure consists of specially designed fittings attached to the Orbiter longerons (not to a bridge fitting). Incorporated into the sill fitting is a separation device that consists of a spring loaded v-band clamp used to connect flanged interfaces of the fitting with a special node attachment fitting. The clamp is separated using a pyrotechnic pin-puller or similar device. The truss node is connected to the fitting through a short adapter strut that has strut end fittings at each end. This adapter strut is manually installed by the astronauts.

Also shown in the figure is the envelope of the RMS and the manipulator positioning retention mechanism (MPM). In the current position of the truss, when it is attached to the Orbiter longerons, the lower arm MPM interferes with the port truss batten as shown. There are two solutions to this problem: One is to increase the length of the adapter struts by approximately three-tenths of a meter (twelve in.) to raise the batten above the MPM envelope, and the other is to move the SAVE assembly fixture forward in the cargo bay approximately three-tenths of a meter (twelve in.) to locate the truss attachment points between the upper arm and lower arm MPM's located at stations 911 and 1189, respectively. The latter solution is recommended so that the truss is as close to the longerons as possible for testing.

Structures and Assembly Verification Experiment (SAVE)

Sill Fitting



WEIGHT STATEMENT SUMMARY

This experiment weight summary is tabulated by work breakdown structure categories. The total weight exceeds the goal of six thousand eight hundred kg (fifteen thousand lbs.) established at the beginning of the study. The assembly fixture contributes approximately forty-two percent of the total weight and is an area where more detailed design and sizing of structural elements for loads and stiffness may result in significant weight savings. The other area that is subject to change is the utility trays. This weight will be determined by the Space Station design.

The subsequent five charts show a further breakdown in the weights of each WBS 1.3 subcategory, with the exception of software.

SAVE
0012

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Weight Statement Summary

BOEING

	Kg	Lbs
1.3.1 Assembly fixture subsystem	3744	8266
1.3.2 Truss structure subsystem	2327	5135
1.3.3 Utility tray subsystem	2625	5793
1.3.4 Instrumentation subsystem	252	557
1.3.5 Excitation subsystem	15	33
Total	8963	19784

WEIGHTS STATEMENT

This chart tabulates the assembly fixture subsystem weights.

Structures and Assembly Verification Experiment (SAVE)

Weights Statement

	Kg	Lbs
1.3.1 Assembly fixture subsystem		
1.3.1.1 Assembly fixture		
Erection frame	680	1500
Pallet subassembly	1502	3316
Diagonal supports	217	479
Truss translation drive system	211	466
Truss node support and guide assy.	129	284
1.3.1.2 Astronaut positioning system		
Drive assembly (Including "Z" drive and rotation drive)	176	389
"L" arm assembly	119	262
Astronaut platform (Including "X" drive)	90	198
1.3.1.3 Component stowage system		
Nodes, Battens and longerons, Diagonals, Tip mass support struts	532	1176
1.3.1.4 Truss lock down fixture		
Orbiter sill hard mounts	89	196
Total	3744	8266

WEIGHTS STATEMENT

This chart tabulates the truss structure subsystem weights.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Weights Statement

BOEING

1.3.2 Truss structure subsystem	Kg	Lbs
1.3.2.1 Node assemblies	95	210
1.3.2.2 Battens, longerons	721	1591
1.3.2.3 Diagonals	558	1232
1.3.2.4 Tip mass Including excitation driver	907	2000
1.3.2.5 Tip mass support struts	46	102
Total	2327	5135

WEIGHTS STATEMENT

This chart tabulates the utility tray subsystem weights.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Weights Statement

BOEING

	Kg	Lbs
1.3.3 Utility tray subsystem		
1.3.3.1 Utility trays, electrical	1450	3200
1.3.3.2 Utility trays, fluid	834	1840
1.3.3.3 Tray support assemblies		
4 point attachment (3 pl)	99	219
Intermediate attachment (4 pl)	20	44
1.3.3.4 Utility tray stowage containers	222	490
Total	2625	5793

WEIGHTS STATEMENT

This chart tabulates the instrumentation subsystem weights.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Weights Statement

BOEING

	Kg	Lbs
1.3.4 Intrumentation subsystem		
1.3.4.1 Static measurement		
Photogrammetry	204	450
Optical targets	Neg.	Neg.
Thermocouples	2	5
1.3.4.2 Dynamic response		
Laser system	5	12
Strain gages, Accelerometers	14	31
1.3.4.3 Data recording and acquisition system	23	50
1.3.4.4 Cabling and attachments	4	9
Total	252	557

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WEIGHTS STATEMENT

This chart tabulates the excitation subsystem weights.

Structures and Assembly Verification Experiment
(SAVE)

Weights Statement

BOEING

	Kg	Lbs
1.3.5 Excitation subsystem		
1.3.5.1 Excitation driver	29*	65*
1.3.5.2 Cabling	15	33
1.3.5.3 Excitation monitoring instrumentation	.4*	1*
1.3.5.4 Power conditioner	5*	10*
Total	15	33

*Included in Tip mass

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EQUIPMENT LIST

An itemized equipment list was generated for each assembly in WBS 1.3. This chart shows the first page of the equipment list as an example. Included in the list are the WBS subsection number, item number, the name of the part, the quantity required, the total weight of those parts, a physical description of the part, an indication of whether the part will be manufactured or bought, and, if the part is to be bought, the name of the manufacturer, its cost and the lead time required. The symbols that precede some of the weights (- >, >> and =>>) indicate various levels of subtotals.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Equipment List

BOEING

WBS NO.	ITEM	PART NAME	QTY	WT (LB)	PHYSICAL DESCRIPTION	MAKE /BUY	IF BUY: MANUFACTURER	COST ($)	LEAD TIME (M)
1.3		PAYLOAD EQUIPMENT	=>>	19784					
1.3.1		ASSEMBLY FIXTURE SUBSYS.	>>	8266					
1.3.1.1		ASSEMBLY FIXTURE	>	6045					
1.3.1.1.1		ERECTION FRAME	-	1500					
	1	FRAME, WELDED	1	1408	WELDED AL RECTANGULAR FRAME	M			
	2	PIVOT PIN FTG	2	48	AL PIVOT PIN FTG, MACHINED	M			
	3	PIVOT PIN	2	44	STEEL PIVOT PIN	M			
1.3.1.1.2		PALLET SUBASSEMBLY, FWD	-	1678					
	1	PALLET STRUCTURE	1	1089	WELDED AL PALLET, LENGTH=112"	M			
	2	TRUNNION PINS	4	128	STEEL TRUNNION PINS (STD)	M			
	3	KEEL PINS	1	32	STEEL KEEL PIN (STD)	M			
	4	TRUN. PIN SUPT STR.	4	46	MACHINED AL SUPT FTG	M			
	5	KEEL PIN SUPT STR.	1	13	MACHINED AL SUPT FTG	M			
	6	ASSY FXT LOCKDOWN	2	24	MACHINED AL MECHANISM	M			
	7	CANISTER ATTACH ASSY	2	312	ROT. MOUNT, BASE, PAD	M			
	8	TIP MASS SUPT. STR.	2	34	AL BRKTS AND LOCKS	M			
1.3.1.1.3		PALLET SUBASSEMBLY, AFT	-	1638					
	1	PALLET STRUCTURE	1	1161	WELDED AL PALLET, LENGTH=112"	M			
	2	TRUNNION PINS	4	128	STEEL TRUNNION PINS (STD)	M			
	3	KEEL PINS	1	32	STEEL KEEL PIN (STD)	M			
	4	TRUN. PIN SUPT STR.	4	46	MACHINED AL SUPT FTG	M			
	5	KEEL PIN SUPT STR.	1	13	MACHINED AL SUPT FTG	M			
	6	ASSY FXT DIAG SUPTS	2	258	WELDED AL TRUSS BRACE	M			
1.3.1.1.4		DIAGONAL SUPPORTS	-	479					
	1	BEAMS	2	117	AL SUPPORT BEAMS	M			
	2	ATTACH FTGS	4	80	AL ATTACH FTG (LWR END)	M			
	3	PINS & LOCKS	4	49	STEEL PINS & LOCKS	M			
	4	BEAM/ASSY FXT FTG	2	154	AL SLIDING ATTACH FTG	M			
	5	BEAM, ERECTION TRACK	2	79	AL TRACK FOR SLIDING FTG	M			
1.3.1.1.5		TRUSS TRANSL. DRIVE	-	466					
	1	DRIVE CROSS ARM	1	172	AL BEAM	M			
	2	NODE CLAMP MECHANISM	2	72	AL/STL CLAMP MECHANISM	M			
	3	DRIVE RAILS	2	136	DRIVE RAILS FOR CROSS ARM	M			
	4	DRIVE UNIT ASSY.	2	50	ELECTRO/MECH DRIVE MECH.	M			
	5	CONTROLS	1	20	ELECTRONIC PACKAGE	M			
	6	CROSS-ARM EXTENS. LOCK	2	16	LOCK MECHANISM	M			

ASSEMBLY SEQUENCE

This chart summarizes the steps in the SAVE assembly sequence. The six charts that follow graphically illustrate the major steps in this process.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Assembly Sequence

BOEING

- Assembly Fixture Stowed in Orbiter
- Assembly Fixture Erected
- Start/Completion of "T"
- Continuation of Truss ("T" Oriented 90^{o} to Orbiter ℄)
- End of 1st Day (Locked Down)
- Testing
- Start of 2nd Day (Assy Position)
- End of 2nd Day (Locked Down)
- Testing
- Stow Assembly Fixture

ASSEMBLY SEQUENCE

The assembly sequence begins with the Orbiter bay doors opening to reveal the packaged SAVE experiment as described in a previous chart.

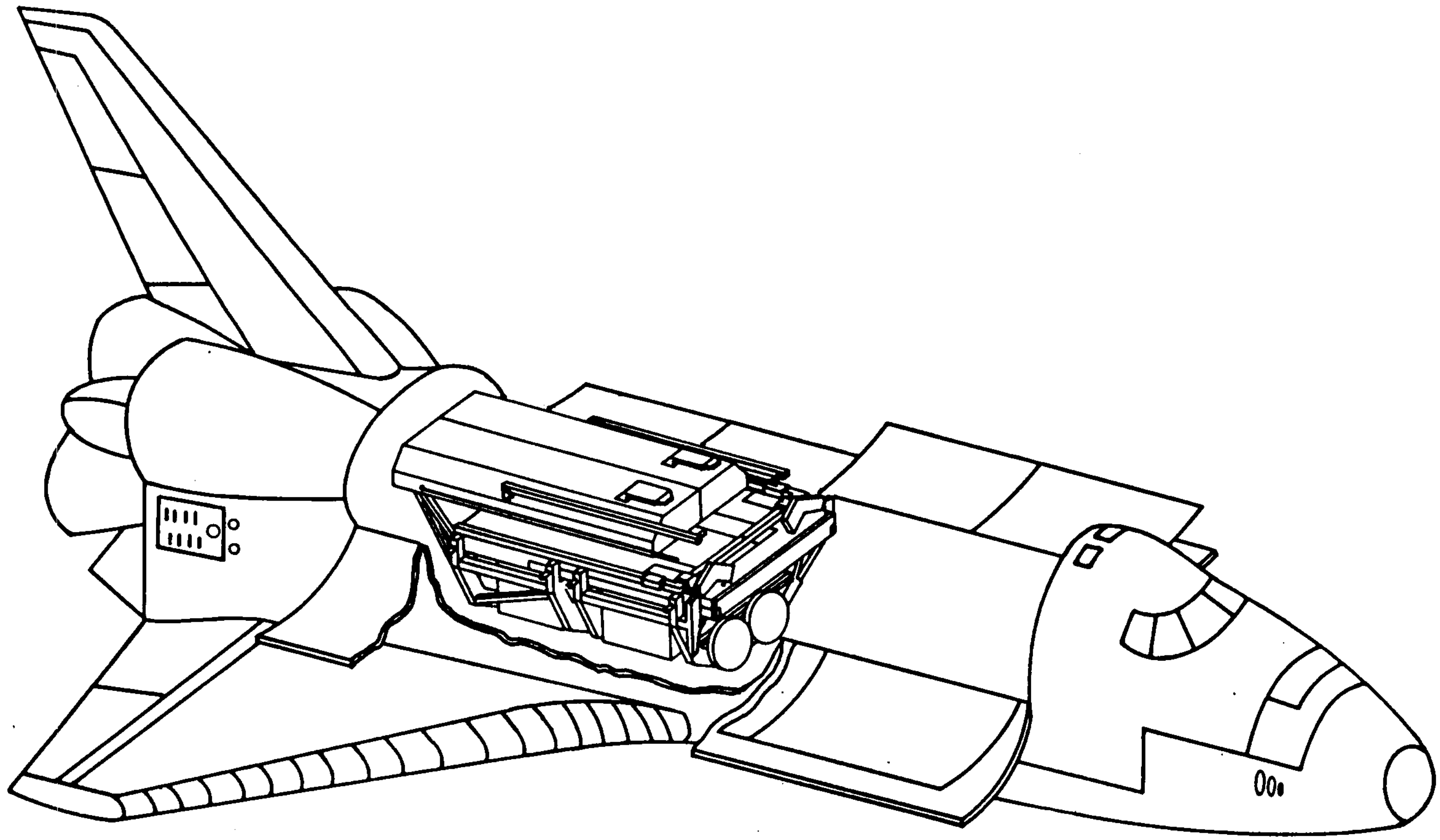
SAVE
0090

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Assembly Sequence

BOEING



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ASSEMBLY SEQUENCE

The next step is to erect the assembly fixture. This sequence show below was established using the assumption that it can be accomplished using the remote manipulator system (RMS). (Note: with the assembly fixture in the aft portion of the cargo bay, some of the prescribed operations may not be within the reach envelope of the RMS). Automated deployment mechanisms, drives, linkages and latches, could be designed into the assembly fixture with corresponding increases in complexity, weight and cost. With either of the above methods, the assembly fixture will be ready for truss assembly before the start of the first EVA. Manual deployment by astronauts is also a possibility, but would require additional EVA time.

1. Rotate stowage canister supports into position and lock.
2. Remove stowage canisters and install into supports.
3. Rotate astronaut positioning arms ninety degrees about y-axis.
4. Raise assembly fixture to vertical position and lock.
5. Extend astronaut positioning arms (y direction) and lock.
6. Rotate astronaut positioning arms one-hundred eighty degrees about y-axis.
7. Extend truss guide rails and lock.

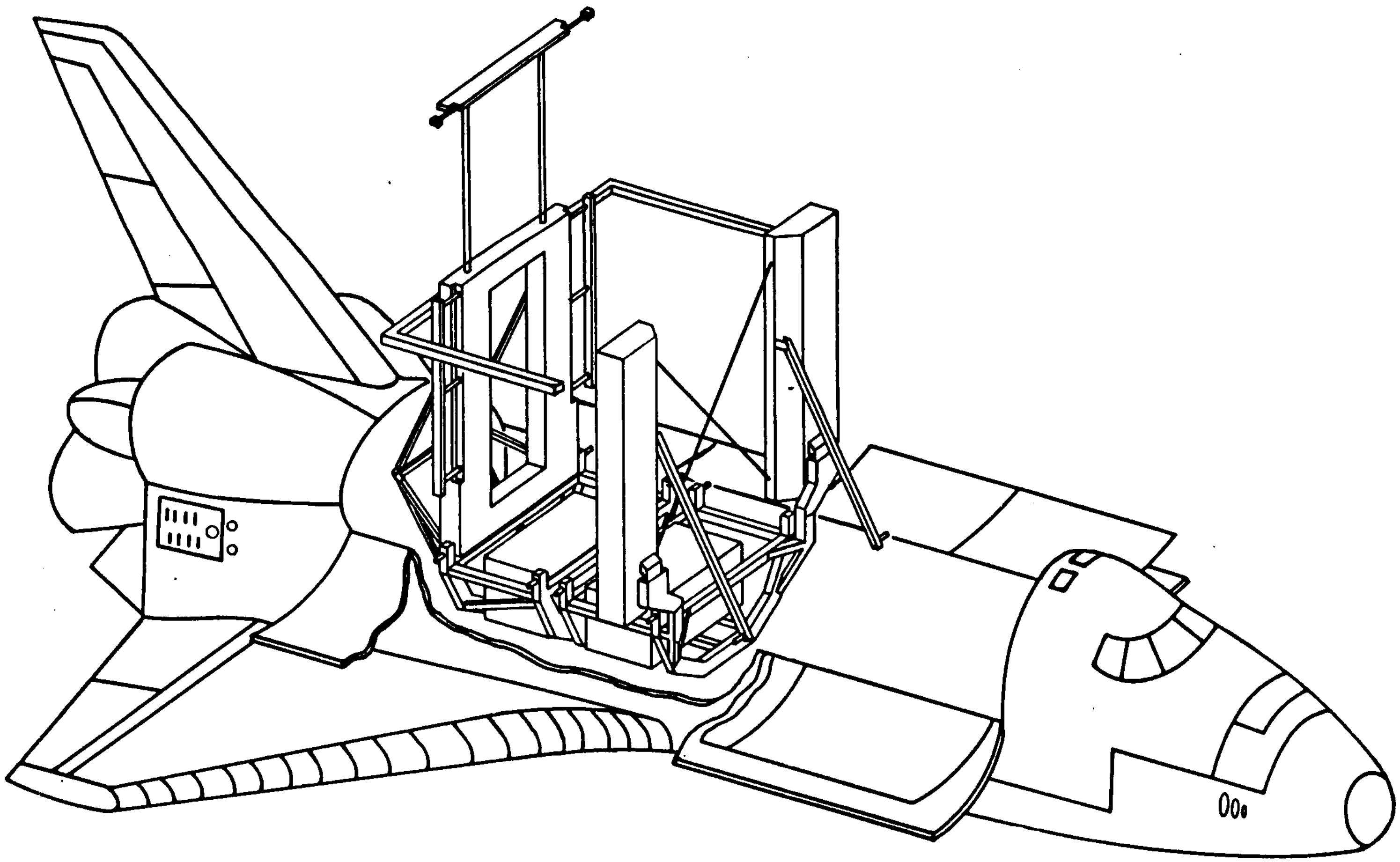
At the beginning of the first EVA, the astronauts connect the braces between the stowage canisters and, if required, the braces from the canisters to the longerons.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Assembly Sequence

BOEING



ASSEMBLY SEQUENCE

The SAVE truss assembly begins with the construction of the "T". After the completion of the first bay, the RMS is used to retrieve and position the tip mass while the astronauts connect it to the truss, as shown in the figure on the left.

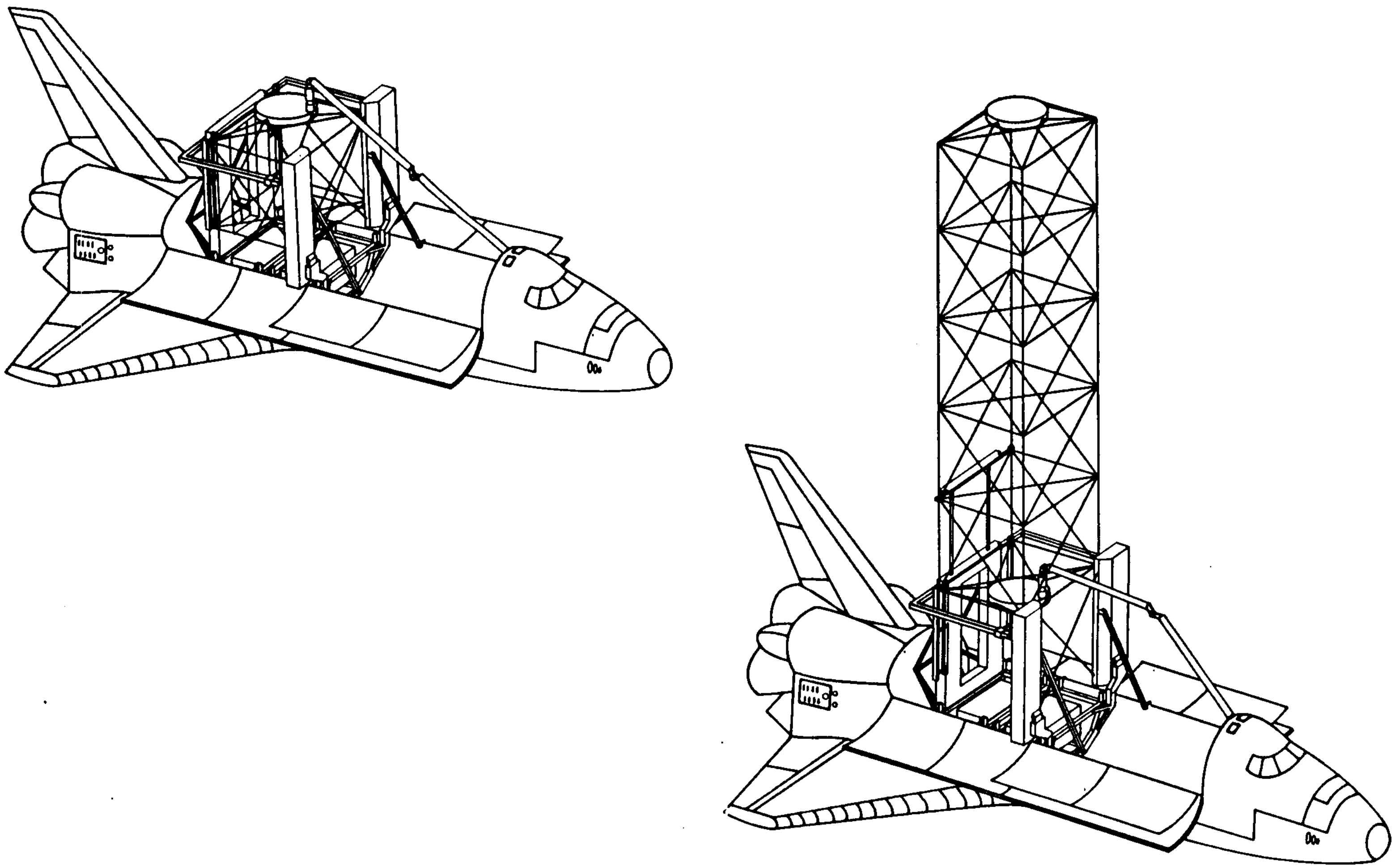
Next, the truss is translated upward five meters using the truss translation mechanism, and another truss bay is assembled below it. This process is repeated until the fifth bay is assembled, with the exception of the forward batten on the fifth bay. It is omitted to provide more room for the RMS to position the other tip mass as shown in the right-hand figure. After the tip mass is connected, the batten is installed.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Assembly Sequence

BOEING



ASSEMBLY SEQUENCE

The "T" structure is removed from the assembly fixture, rotated as shown in the figure and reattached to the assembly fixture. This step is illustrated as being accomplished by the RMS using a guide pin as an attachment point. The position of the experiment in the cargo bay will determine whether the RMS reach envelope is sufficient for this task. An alternate approach is to rotate and reattach the truss manually with one astronaut in the mobile foot restraint (MFR) and the other in a foot restraint on the assembly fixture.

SAVE
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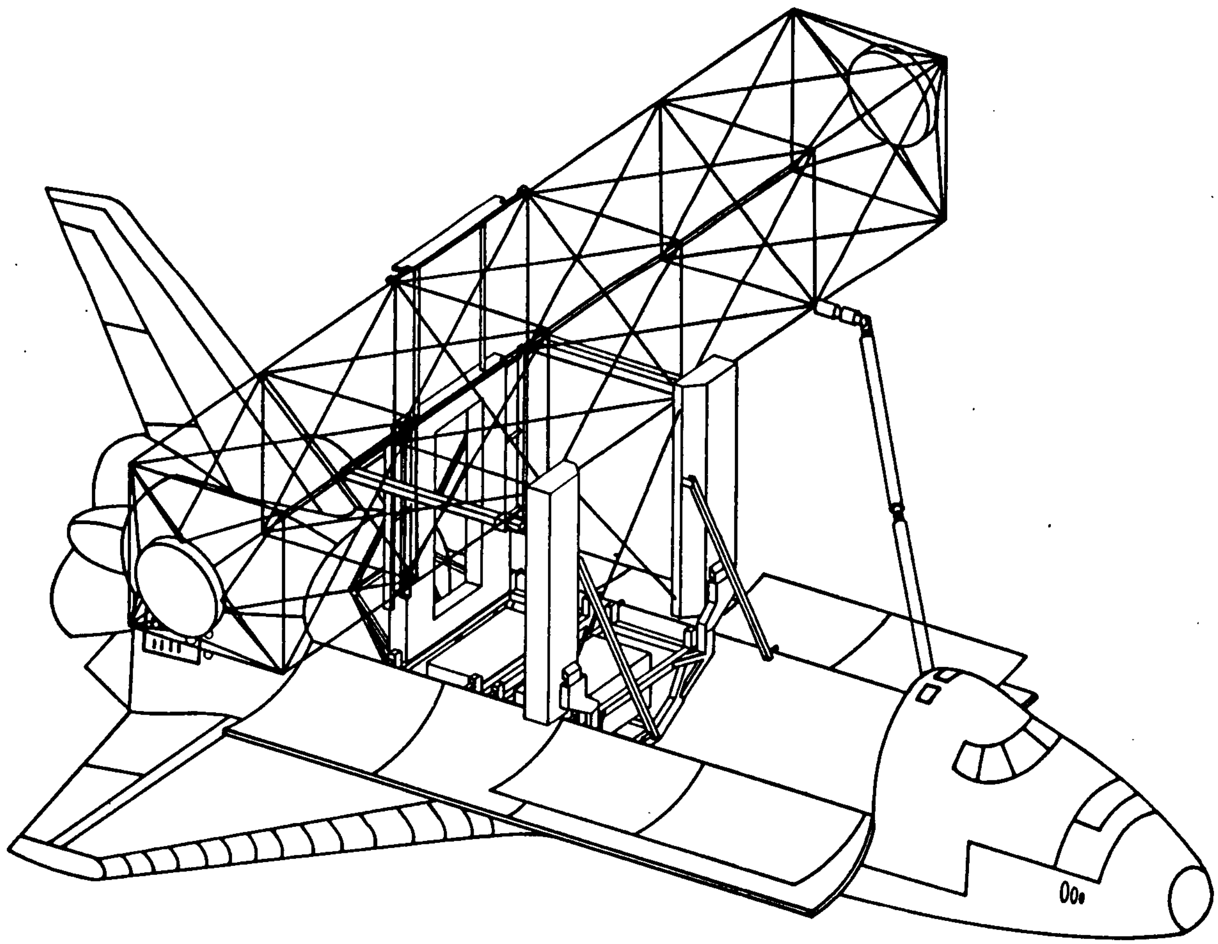
Structures and Assembly Verification Experiment (SAVE)

Assembly Sequence



ASSEMBLY SEQUENCE

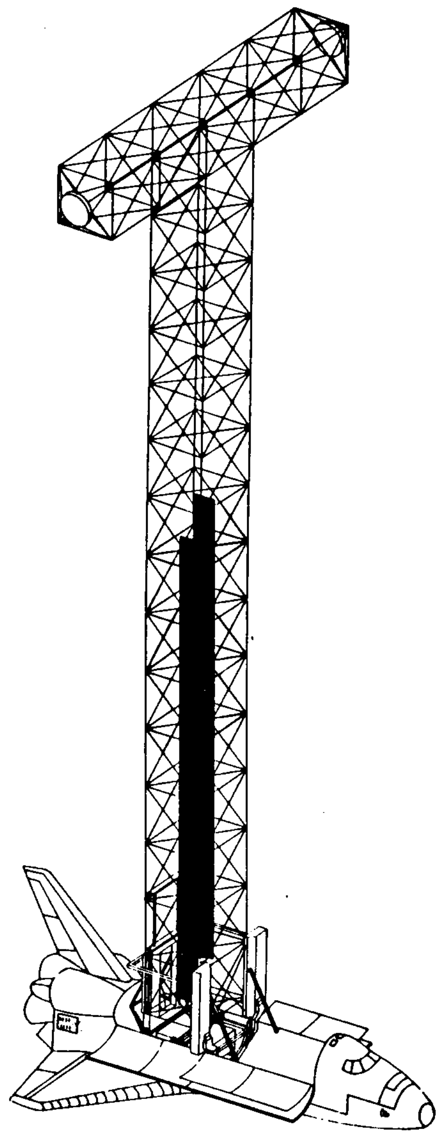
Assembly of the truss continues until seven more bays are added to the structure, as shown on the left. The truss translation mechanism is then used to translate the truss downward, and the astronauts attach it rigidly to the sill attachment fixtures. The truss translation mechanism releases its attachment to the truss, and a section of the truss guide rail opens to prevent constraints on the guide pin located in the guide rail. The truss, as shown in the figure on the right, is now ready for dynamic tests. The completion of member-out dynamic tests concludes the first day of EVA.

SAVE
0098

Structures and Assembly Verification Experiment
(SAVE)

Assembly Sequence

BOEING



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CONCLUSIONS AND RECOMMENDATIONS

As a result of the design effort, it is concluded that the experiment is feasible. Twenty bays of Space Station truss structure can be assembled by two astronauts in two six-hour EVA periods and tested to determine its characteristics. The experiment occupies half of the Orbiter payload bay, but its weight exceeds the established goal. The assembly fixture and procedures simulate the assembly of the Space Station truss structure.

To simplify the design and minimize weight and cost, it is recommended that assembly fixture deployment drive mechanisms be minimized and that the RMS be used for assembly fixture set-up to minimize EVA time. The ability of the RMS to accomplish this task is an area that requires more investigation.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Conclusions and Recommendations

BOEING

Conclusions

- Experiment Concept Feasible
  - 20 Bay Total
  - 24 EVA Man Hours
  - On-orbit Structural Characterization
- Weight Exceeds 15,000 Pound Goal
- Stow Within ½ Payload Bay
- Assembly Fixture Simulates MRMS Function

Recommendations

- Minimize Deployment Drive Systems
  - Simpler Construction
  - Simpler Design
- Maximize Use of RMS
  - Fixture Set Up (Reduces EVA Timelines)
  - Repositioning of "T"

PRELIMINARY TIMELINE ASSUMPTIONS

EASE/ACCESS data and videotapes were used to establish EVA start and completion points and to determine strut and node installation timelines. Two forward located stowage containers were assumed, therefore translation of equipment from the forward to aft positions is necessary. Utility tray timelines do not include connecting wiring or fluid lines.

Manrated RMS timelines were developed prior to the EASE/ACCESS mission. These were used for determining translation times for the astronaut positioning system.

Maximum use of the RMS was assumed to reduce EVA timelines. RMS operations include erection of the assembly fixture and setup of work stations. These operations are performed prior to the start of EVA.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Preliminary SAVE Timeline Assumptions

BOEING

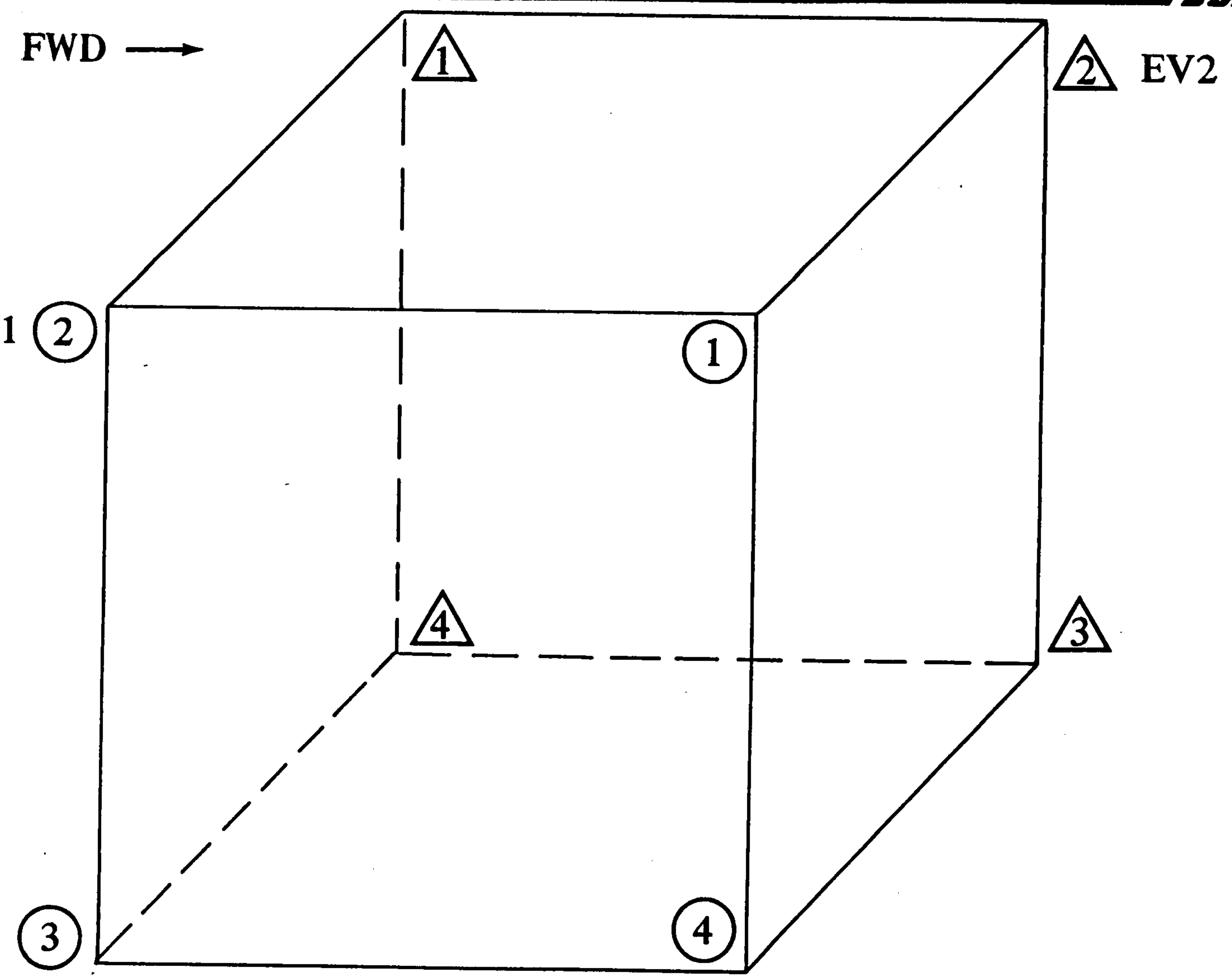
- Initial EVA tasks start when battery power turned on.
- Final EVA tasks end with connection of SCU.
- No contingency time is included for problems, assumes everything goes smoothly.
- Strut and nodes times are based on preliminary EASE and ACCESS video tape analysis.
- Struts and nodes are stowed in 2 containers located forward of the assembly fixture.
- Strut and node times assume that they are presented where and when needed, in the correct order, and crewmembers do not have to egress foot restraints.
- Construction fixture and utility tray times are based on preliminary designs.
- No time alloted for connecting utility lines or wires.
- Assumes instrumentation is pre-integrated with structural members.
- Safety tether attach points are a part of the astronaut positioning system.
- No time alloted to EMU status checks or breaks.
- EVA translation velocity = .24 m/s (.8 fps)
- Shuttle RMS power up, checkout, and translation times not charged to EVA.

ASSEMBLY METHOD "A"

Designators are used for the two astronauts. EV1 is located on the starboard side of the Orbiter payload bay and EV2 is located on the port side. The astronaut sequential motions are depicted by numerical sequence. As shown, they start at opposite corners on the same elevation and continue this opposed position routine to conclusion of bay construction. This approach requires extra translations by EV2 to unlock the forward upper canister lockouts and to translate equipment from the forward stowage canister to the aft starting position.

Structures and Assembly Verification Experiment (SAVE)

Assembly Method "A"



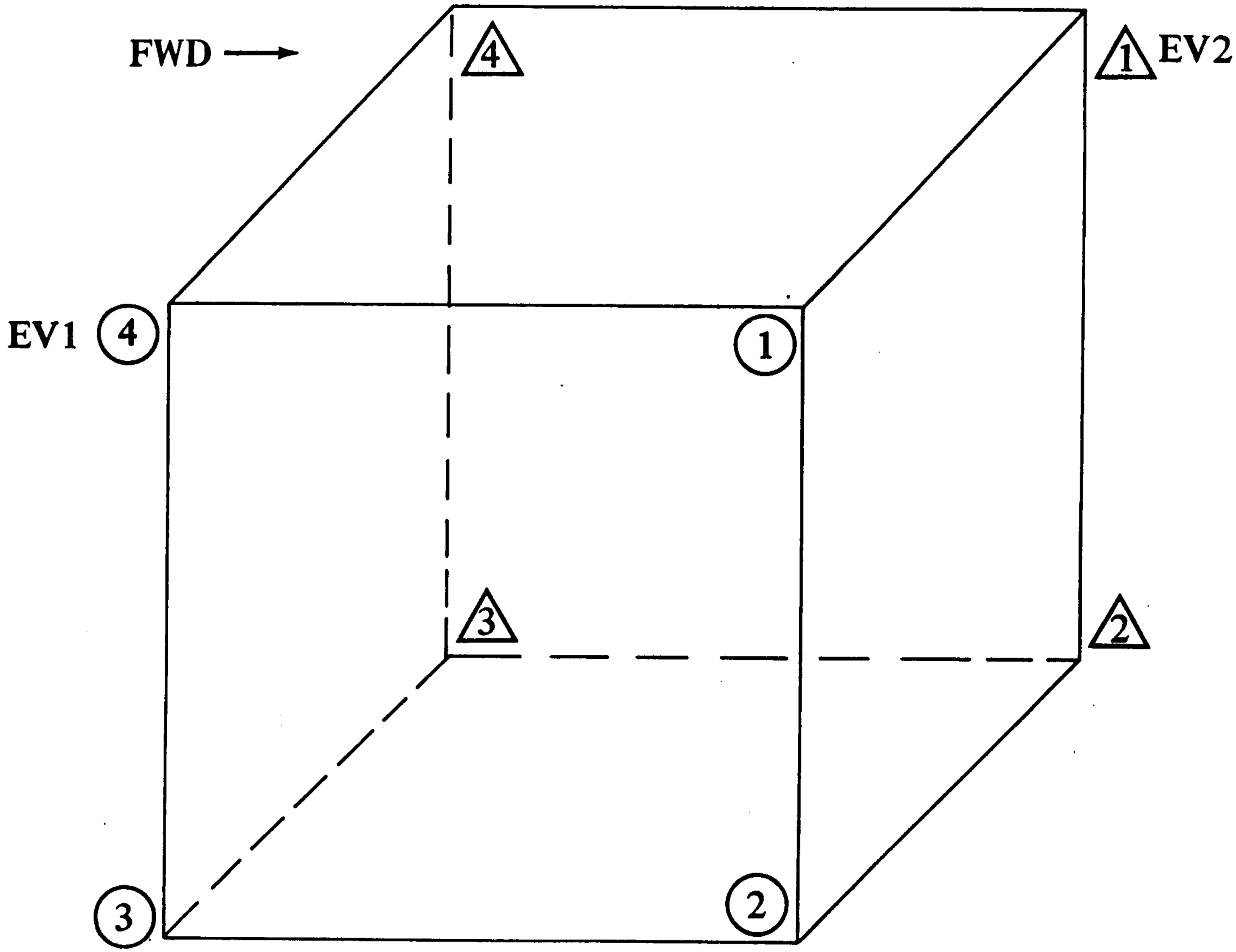
ASSEMBLY METHOD "B"

Assembly Method "B" solves the translation problem previously described for Method "A". Method "B" was selected for this study and used to develop timelines. The assembly sequence starts at the forward upper position for both EV1 and EV2. Both astronauts are located adjacent to the canister lockouts and to the equipment located in the stowage canisters for positions one and two. Equipment for positions three and four is carried during translation and stowed in a convenient location. A non-working translation from position four back to position one is required to unlock, in preparation for raising the completed bay. The routine is then repeated for the next bay, except fewer parts are carried because the nodes at position three (now position four) are already in place.

Structures and Assembly Verification Experiment (SAVE)

Assembly Method "B"

BOEING



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ASSEMBLY SEQUENCE

This assembly sequence represents the second and subsequent bays in a member-by-member installation sequence. The timelines of the following chart represent the assembly sequence portrayed here. The black arrows and small numbers identify the numerical order of member assembly and the position from which the astronaut performs the task. For example, EV2 installs the diagonal first and the longeron second, then moves to the lower position two and installs diagonal two, batten three and diagonal four in that order. EV1 performs similar tasks and also installs the free ends of parts that were installed by EV2, such as the first diagonal at position one.

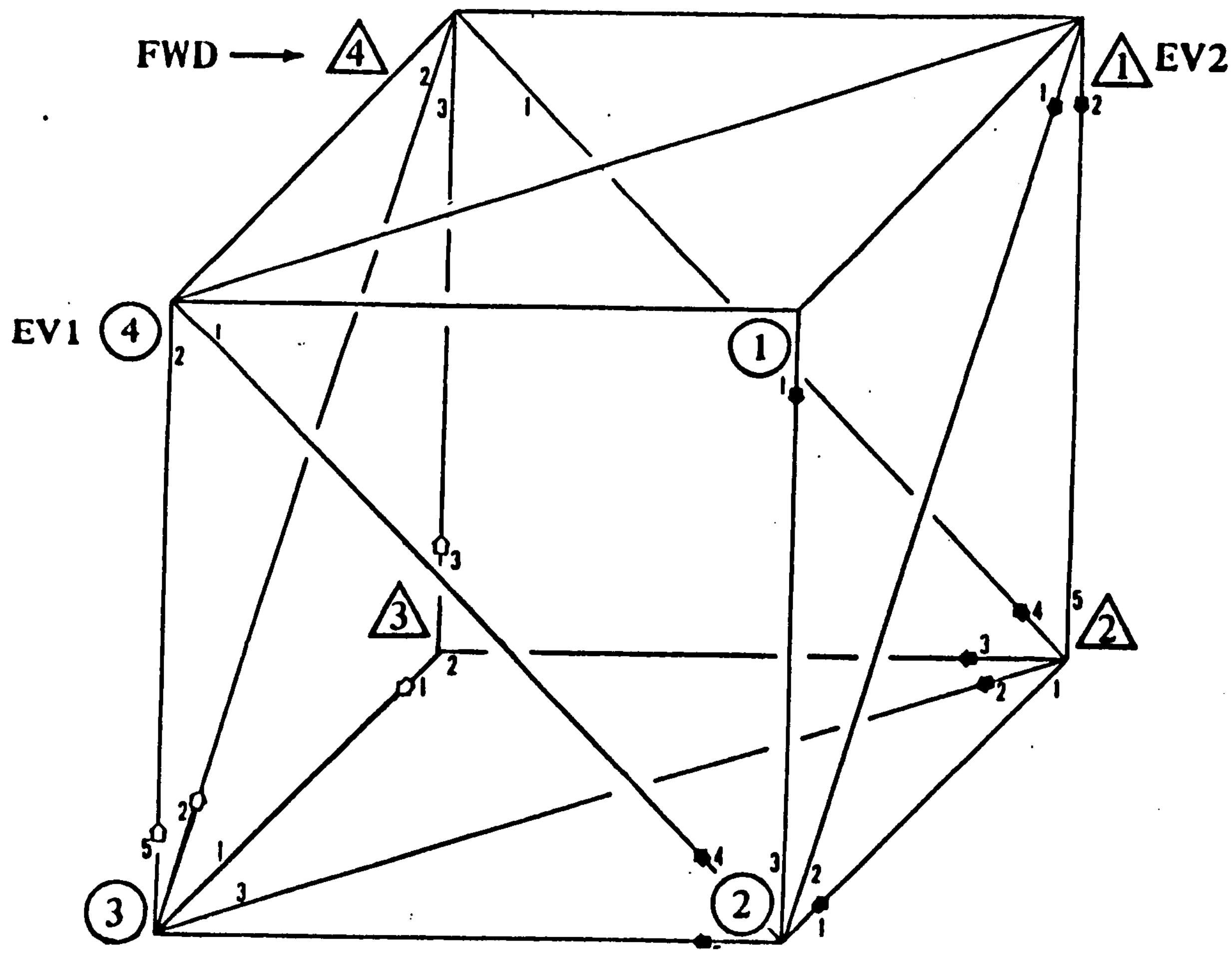
The open arrows at the number three position depict the struts that are obtained at position two temporarily stowed and installed after the astronauts have translated to position three.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Assembly Sequence (Bay 2)

BOEING



TIMELINE

The timelines shown on the figure represent the assembly sequence described on the previous chart and are identical for bays two through twenty of the experiment. The times shown are in seconds. Total time to construct one bay is approximately fifteen minutes and seventeen seconds.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Timeline

BOEING

CONSTRUCT BAY 2

	EV 1	SEQ	EV 2	SEQ
obtain diagonal			10	1
install diagonal			50	1
obtain longeron	10	1	10	2
install longeron	50	1	50	2
translate V 5m to position 2	23		23	
attach instrumentation cable			30	
obtain node	10		10	
install node	20		20	
obtain batten	10	1		
install batten	50	1		
attach batten			20	1
attach diagonal	20	2		
obtain diagonal	10	4	10	2
install diagonal	50	4	50	2
attach longeron	20	3	20	5
obtain batten	10	5	10	3
install batten	50	5	50	3
obtain diagonal			10	4
install diagonal			50	4
obtain longeron	10		10	
temporary stow longeron	50		50	
obtain diagonal	10			
temporary stow diagonal	50			
obtain batten			10	
temporary stow batten			50	
obtain node for position 3	10		10	
temporary stow node	20		20	

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Structures and Assembly Verification Experiment (SAVE)

Timeline Continued

BOEING

CONSTRUCT BAY 2 CONTINUED

	EV 1	SEQ	EV 2	SEQ
translate H 5m to position 3	23		23	
obtain node from temporary stowage	10		10	
install node	20		20	
obtain temporary stowed batten			10	1
install batten			50	1
attach batten	20	4	20	2
obtain temporary stowed diagonal	10	2		
install diagonal	50	2		
obtain temporary stowed longeron	10	5	10	3
install longeron	50	5	50	3
attach diagonal	20	3		
attach batten	20	1		
translate V 5m to position 4	23		23	
attach diagonal	20	1	20	1
attach diagonal			20	2
attach longeron	20	2	20	3
translate to position 1	23		23	
unlatch canister hold downs	10		10	
raise bay	25		25	
latch canister hold downs	10		10	
TOTAL TIME BAY 2	847		917	

TOTAL TIME TO CONSTRUCT BAY 2 = 15.28 min

EVA TIMELINE - FIRST DAY

First day timelines represent activity to construct the first twelve bays and attach them rigidly to the Orbiter sills. Also included is the assembly of the "T" portion, tip masses, and the rotating of the "T" to the horizontal position. Time has been allocated for removal and replacement of specific truss elements to support the test program. At conclusion of this EVA, half of the structure has been built, but no utility trays have been installed. The first item, translation time, was derived from study of the EASE/ACCESS times. Assembly fixture setup is accomplished in large by the RMS before EVA begins. The three minutes shown involves attaching canister braces, translating and ingress into the astronaut positioning system foot restraints. The final EVA tasks involve translation, ingress and repressurization in the airlock. The total time used is ninety-three percent of the budgeted EVA time.

Structures and Assembly Verification Experiment (SAVE)

EVA Timeline - 1st Day

Task	Time (min.)
Depress, egress and translate to workstation	30
Assembly fixture and workstation set up	3
Construct bay 1	20
Install tip mass	12
Construct bays 2-5	61
Install tip mass	12
Reposition truss	5
Construct bays 6-12	106
Attach truss to orbiter sills with tie down struts	4
Conduct dynamic tests with 1 longeron out	35
Conduct dynamic tests with 1 diagonal out	35
Final EVA tasks	15
Total time	338 min. =5.6 hrs.

EVA TIMELINE - SECOND DAY

Eight bays are constructed during this EVA. The first of a series of utility trays is "hard" mounted to the twelfth bay of the preceding days work. Each astronaut attaches a tray to his respective side. "Soft" tray mounts and tray attachments are installed on Bays thirteen through fifteen. Another hard mount is provided at Bay sixteen and soft mounts are located on Bays seventeen through nineteen. A final hard mount is made on Bay twenty.

The truss is attached to the sills and dynamic tests similar to the first day's EVA are conducted. The stowage canister braces are disconnected and stowed prior to ingress and repressurization. It is expected the RMS will stow the canisters and assembly fixture after the truss experiment has been jettisoned. Total time used is ninety-two percent of budgeted EVA time.

Although a free flyer version of the experiment is described in this report there has been no EVA time considered for attaching the spacecraft bus, connecting lines, checkout and power-up.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

EVA Timeline - 2nd Day

BOEING

Task	Time (min.)
Initial EVA tasks	30
Workstation configuration setup	3
Release truss from sills and position for assembly	3
Install utility tray attachment (hard) and attach trays	19
Construct bays 13-15 including tray supports and attach trays	59
Construct bay 16 and install tray hard mount	28
Attach utility trays to bay 16	4
Construct bays 17-19 including tray supports and attach trays	59
Construct bay 20	15
Install utility tray attachment (hard) and attach trays	17
Attach truss to orbiter sills	4
Conduct dynamic tests with one longeron out	35
Conduct dynamic tests with one diagonal out	35
Remove and stow canister braces	3
Final EVA tasks	15
Total time	329 min. =5.5 hrs.

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RECOMMENDATIONS

Further study is required to develop a more accurate estimate of timelines. The areas requiring major emphasis are: utility tray installation, attachment and connections; canister translation and anchoring features to provide astronauts freedom of motion; canister automated delivery system for truss elements; tip mass trades on stowage locations, manual and RMS assisted installation and multiple versus single tip masses.

One G tests and simulations are highly recommended to validate the functions that have been assigned to the RMS and to develop more timeline fidelity. Of interest are the times required for setup of assembly fixtures and stowage containers and installing the tip mass.

SPACE STATION

SAVE
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Structures and Assembly Verification Experiment (SAVE)

Recommendations

BOEING

- Expand Utility Tray Study
  - Impact of Folding vs Straight Sections on Timelines
  - Impact of Connecting Techniques
    - Tray to Tray
    - Tray to Truss

- Expand Canister Study
  - Placement and Handrail Requirements
  - Degree of Automation
  - Impact on Timelines

- Further Define Tip Mass Installation Technique
  - Verify Capability of RMS vs Astronaut Safety
  - Impact on Total Timeline

- Validate Timelines and Concept Through 1-G Simulations
  - RMS Activities
    - Set Up Assembly Fixture
    - Set Up Stowage Container
    - Install Tip Mass
    - Rotate "T"

RECOMMENDATIONS

One G and neutral buoyancy tests are recommended to develop timeline detail for the listed activities. Foam core low fidelity mockups could be used in One G with a gloved or suited astronaut to provide detail on handling members, connecting and deploying instrumentation wiring and attaching utility trays.

The astronaut positioning system should be studied to determine possible advantages of adding degrees of freedom in rotation. There is a trade between added system complexity/cost and reduced timelines. A preliminary set of requirements should be established for a positioning system astronaut hand controller.

SPACE STATION

SAVE
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Structures and Assembly Verification Experiment (SAVE)

Recommendations (Cont'd)

BOEING

- EVA Activities
  - Truss Assembly
  - Tip Mass Installation
  - Utility Tray and Attachment Structure Installation
  - Instrumentation Cable Deployment
  - Truss Rotation (To Optimum Free-Flyer Orientation)
  - Investigate Techniques of Hardmounting Truss to Sill
  - Further Define Astronaut Positioning System.
    - Study Feasibility of Providing Rotation Capability
    - Investigate Hand Controller Requirements

OVERALL TEST MATRIX

This matrix is a broad look at the ground and flight testing of truss and assembly fixture hardware envisioned for the Space Station program. For each of five areas of interest, applicable arenas for ground testing are identified for each sub-topic, culminating in flight experiments. Ground tests can be used for components and on sub-scale or full-scale assemblies. Neutral buoyancy simulations are valuable in establishing operational techniques and procedures. Full scale testing of the truss is limited to a few bays due to its large size and the limitations of facilities. Although sub-scale test articles are not mandatory for the experiment, they could be used, if available, for improving dynamic characterization and prediction methods.

On-orbit structural characterization tests for the experiment truss structure are examined in more detail in the following pages.

SAVE
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Structures and Assembly Verification Experiment (SAVE)

Overall Test Matrix

BOEING

Area of Interest	Component	Ground: Sub Scale	Ground: Full Scale	NB	Flight
Structures & Mechanisms					
Truss	X		X*		X
Assembly Fixture	X		X		X
Construction Aids	X		X		X
Utilities Attachment	X		X		X
Storage/Dispenser	X		X	X	X
Operations					
Assembly Fixture Depl.			X	X	X
Truss Assembly			X*	X*	X
Macro Assembly				X*	X
Utilities Installation			X*	X*	X
Maintenance/Repair			X	X	X
Structural Charact.					
Static (Mass, Stiffness)	X	X	X*		
Dynamic	X	X	X*		X
Prediction Methods	X	X	X*		
Test Equipment					
Instrumentation	X	X	X	X	X
Excitation Methods	X	X	X		X
Free-Flyer					
Materials	X				X
Micrometeoroid Prot.	X				X
Control System	X				X
Dynamics					X

*Small number of truss bays

Note: Assumes availability of sub-scale truss for ground testing

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STRUCTURAL CHARACTERIZATION TESTS

The two objectives of the on-orbit characterization tests are to determine the structure's static and dynamic characteristics.

Static measurements can be used to determine the as-built accuracy and thermal deformation of the test article. The redundant nature of the truss and manufacturing tolerances contribute to potential inaccuracies in overall truss dimensions and straightness. In addition, thermal gradients as the truss passes from shadow to full sunlight will result in deformations that, when applied to the Space Station, may have an effect on Space Station subsystems and the pointing accuracy of attached experiments.

The measurement of dynamic characteristics is desired for several truss configurations. Partial and full length tests will determine the effect of truss length and, therefore, frequency on the dynamic behavior of the truss. By testing the truss with various struts removed, the effect of members damaged by micrometeoroid or debris damage can be determined. Also the extent of preload at the orbiter longeron attachment caused by the indeterminate nature of the truss can be evaluated and the analytical model can be verified. The contribution of the utility trays to the dynamics of the truss, in terms of mass, stiffness and damping, can be assessed by testing the truss with and without utility trays installed.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Structural Characterization Tests

BOEING

- Static Shape
  - As-built dimensional accuracy
  - Thermal deformations
- Dynamic Tests
  - Partial and full length
  - Members out
  - Utility trays on/off

UTILITY TRAY OPTIONS

Two utility tray options were considered:

1. Trays installed on one face of the truss along its full length.

2. Trays installed on two opposite sides of the truss along the eight bays closest to the Orbiter.

Both options can be used to demonstrate the procedures and techniques necessary to install utility trays, and allow the determination of the structural dynamic characteristics of the truss with utility trays in place. However, the mass distribution created by option one results in higher truss loads due to PRCS firings since the center of mass of the trays is located farther away from the Orbiter attachment point. The tray mass is also offset from the truss centerline, creating more coupling between the bending and torsion modes. Option two, on the other hand, allows testing of the truss with trays off (eight bay "T" at the end of the first EVA) and with trays on (sixteen bay "T" at the end of the second EVA). The position of the trays also reduces the truss loads due to PRCS firings and results in a more symmetrical configuration that is representative of the Space Station. Therefore, option two was selected for the SAVE experiment.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Utility Tray Options

BOEING

Install Trays Full Length of Truss On One Face	Install Trays on Bottom Half of Truss on Two Faces (Opposite Sides)

• Demonstrates tray installation procedures
  • Trays installed by one astronaut
• Allows determination of tray contribution to dynamics
	• Demonstrates tray installation procedures
	  • Balanced EVA workload
	• Allows testing of truss with & without trays
	  • EVA 1 - 8 bay "T" without trays
	  • EVA 2 - 16 bay "T" with trays on portion of truss with high strain energy

• High truss loads due to primary RCS • Mass offset from truss centerline	• Lower primary RCS loads • More symmetrical • More representative of space station

SELECTED CONFIGURATION

STRUCTURAL CHARACTERIZATION TESTS

The on-orbit test configurations for the truss are shown in this figure. At the end of the first EVA, the test configuration is an eight-bay "T" (eight bays long with an additional two bays on each side to form the "T"). Static shape measurements will be accomplished to determine its as-built dimensional accuracy and to obtain thermal deflection data. Dynamic tests will be conducted to determine its dynamic characteristics and will include tests with various individual truss members removed from the bottom bay. An excitation system located in the two tip masses will be used to excite the x-z and y-z plane bending modes (actuators in-phase) and the torsion modes (x-direction actuators out-of-phase). This configuration results in test data without utility trays installed.

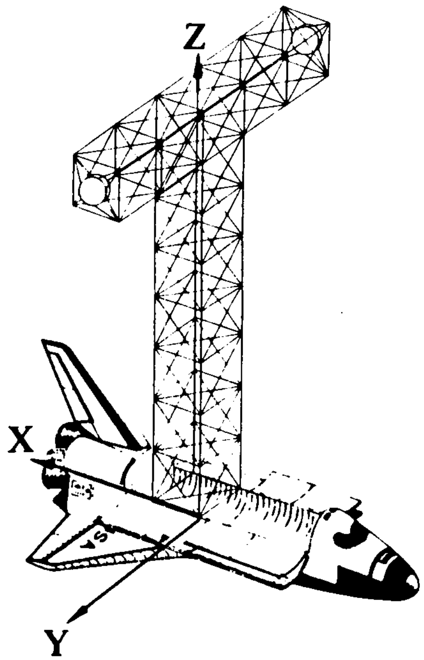
During the second EVA, the remaining eight bays of the truss are constructed and utility trays are installed. The static and dynamic tests are then repeated to obtain structural characterization data that include the effects of utility trays.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

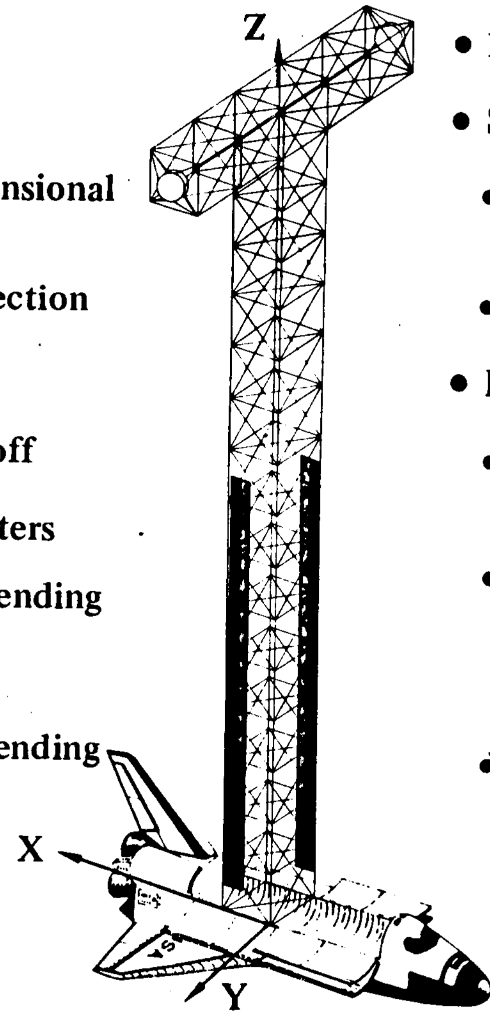
Structural Characterization Tests

BOEING



1st EVA

- 8 bay "T"
- Static shape
  - As-built dimensional accuracy
  - Thermal deflection
- Dynamic test
  - Utility trays off
  - Tip mass exciters
    - X-Z plane bending
    - Torsion
    - Y-Z plane bending
- Also conduct tests with individual members out (bottom bay)



2nd EVA

- 16 bay "T"
- Static shape
  - As-built dimensional accuracy
  - Thermal deformations
- Dynamic test
  - Utility trays on lower 8 bays
  - Tip mass exciters
    - X-Z plane bending
    - Torsion
    - Y-Z plane bending
- Also conduct tests with individual members out (bottom bay)

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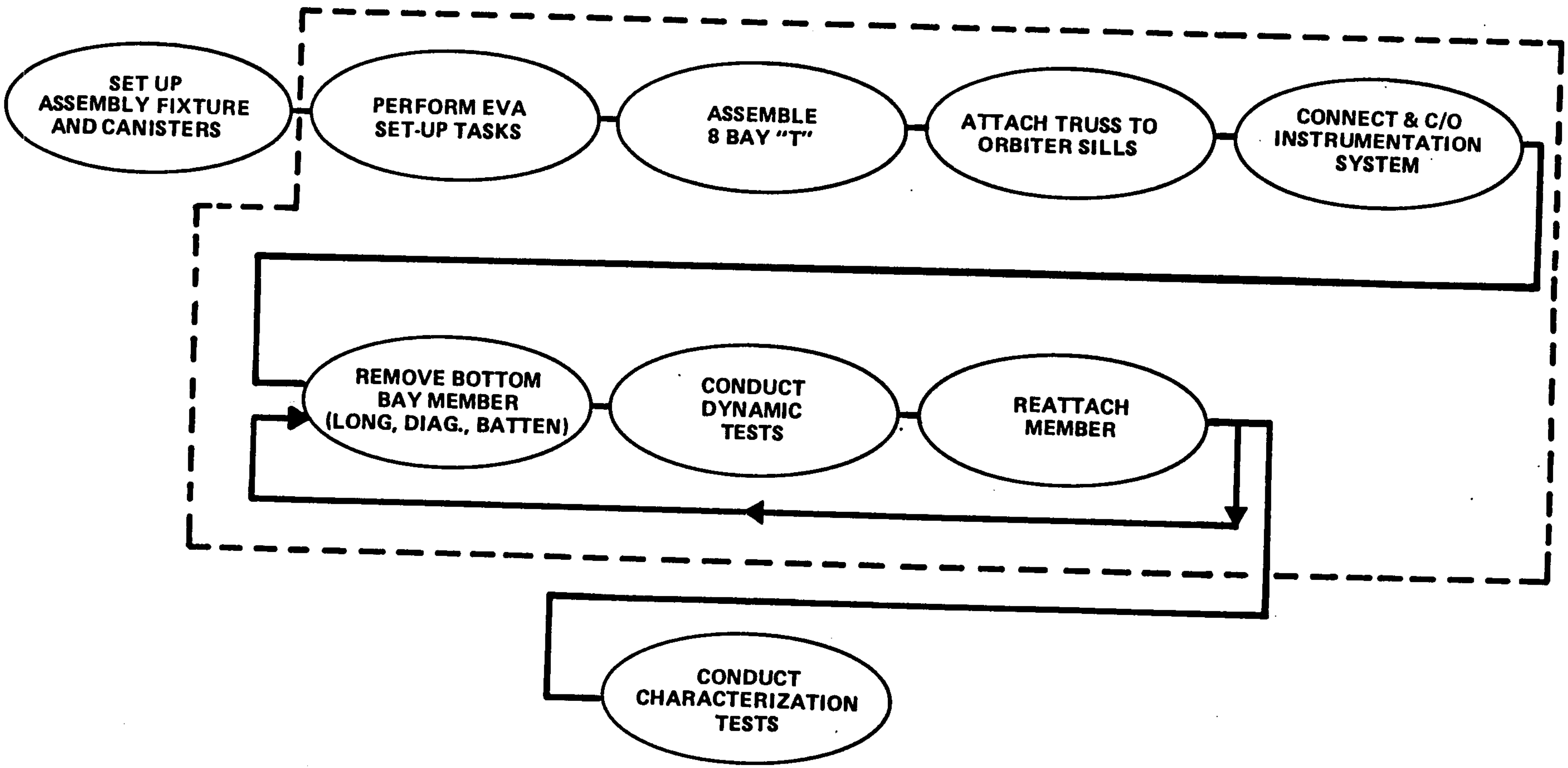
EXPERIMENT TASK FLOW - FIRST EVA

Prior to the first EVA, the major portion of the assembly fixture deployment and stowage canister installation is accomplished either automatically or by using the RMS. The EVA activity (enclosed in dotted lines) begins by completing any assembly fixture and canister set-up tasks that require EVA. The eight bay "T" is assembled and is then attached rigidly to the Orbiter longerons. After the instrumentation system is connected to the data acquisition system, the astronauts remove individual members from the bottom bay of the truss and dynamic tests are conducted. After cargo bay clean-up operations, the astronauts return to the crew compartment, and dynamic tests of the complete eight bay "T" configuration are conducted.

Structures and Assembly Verification Experiment (SAVE)

Experiment Task Flow - EVA 1

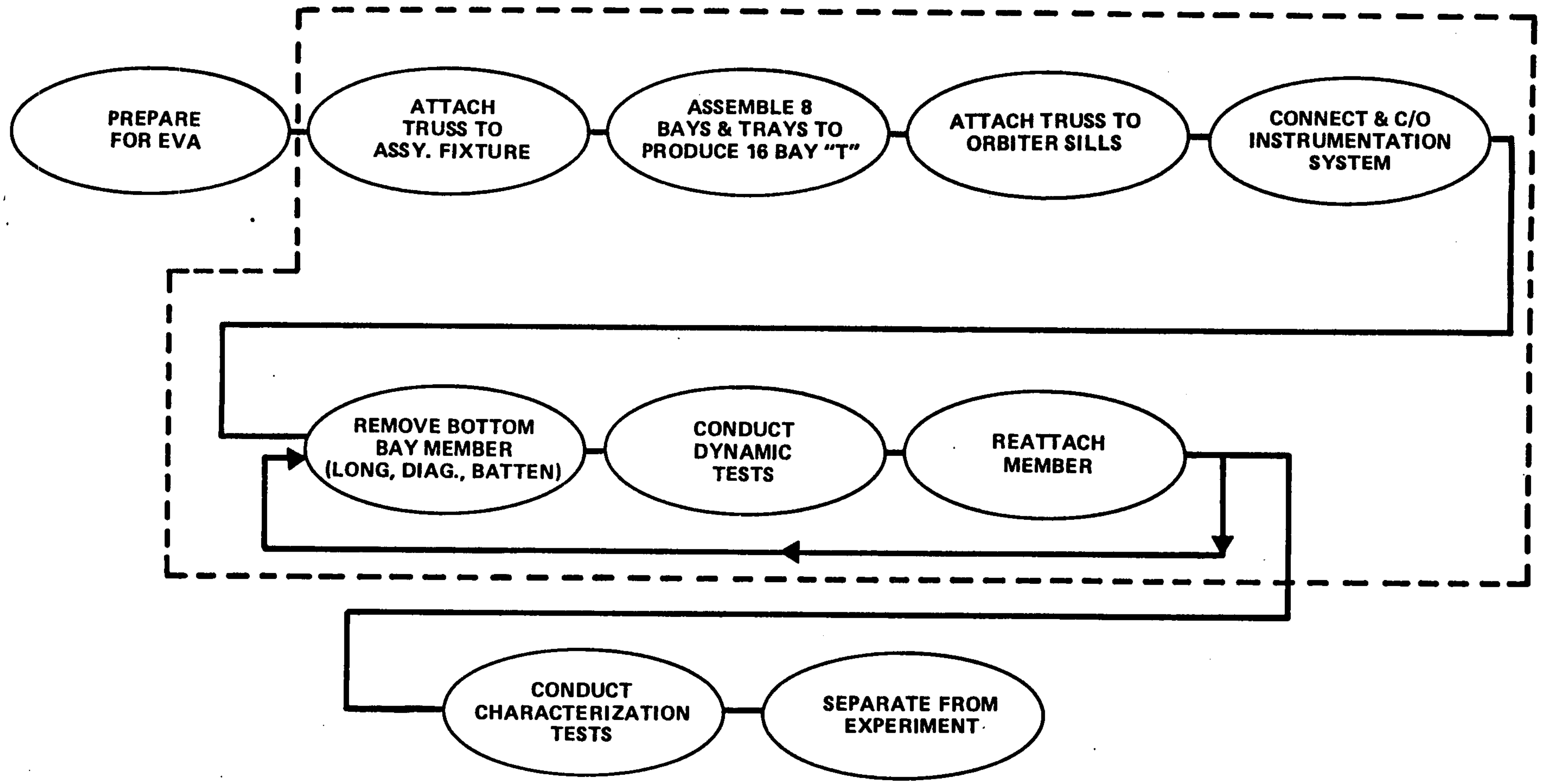


EXPERIMENT TASK FLOW - SECOND EVA

Following EVA preparations, EVA two begins by reattaching the eight bay "T" to the assembly fixture. The utility trays are attached to the bottom bay and the assembly of eight bays, including utility trays, is accomplished. The truss is again attached rigidly to the Orbiter longerons. After the instrumentation system is connected to the data acquisition system, the astronauts remove individual members from the bottom bay of the truss and dynamic tests are conducted. After cargo bay clean-up operations, the astronauts return to the crew compartment, and dynamic tests of the complete sixteen bay "T" configuration are conducted. The truss is then separated from the Orbiter, and the assembly fixture is restowed by means of the RMS for return to earth.

Structures and Assembly Verification Experiment (SAVE)

Experiment Task Flow - EVA 2



DYNAMIC TEST

The excitation system for the dynamic tests will be linear force actuators located in both tip masses. x-direction actuators will act in phase to excite x-z plane bending, and out of phase to excite the torsion modes. A single y-direction actuator will be used to excite y-z plane bending. The use of the Orbiter vernier reaction control system (VRCS) for inducing test loads was considered but was discarded due to controllability limitations.

Three levels of excitation will be used to determine nonlinear effects that may occur in the structure. These levels will be chosen to produce truss member loads that are representative of loads that will occur during day-to-day operation of the Space Station. The nominal Space Station load postulated is approximately four hundred forty-five Newtons (one hundred pounds). Tests will also be conducted at one-third and three times that load.

Instrumentation installed during the assembly of the truss will include accelerometers to measure linear and angular accelerations, strain gauges to measure truss member loads, thermocouples to correlate thermal deformation measurements, load cells to measure Orbiter interface reaction loads, and a laser optical system to measure dynamic displacements.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Dynamic Test

BOEING

- Excitation - Tip mass linear actuators
  - X-Z plane and Y-Z plane bending
  - Torsion
- Test Amplitude (sine sweep)
  - 1/3 typical Space Station load
  - Typical Space Station load - 445N (100 lb)
  - 3x typical Space Station load
- Instrumentation
  - Accelerometers (linear and angular)
  - Strain gauges
  - Thermocouples
  - Load cells
  - Laser optical displacement

TEST INSTRUMENTATION

The location of test excitation and instrumentation are shown in this figure. The tip masses contain the excitation system as well as triaxial accelerometers. Strain gauges, thermocouples and other accelerometers are located at five stations along the truss. These stations are at the base of the truss and at the twenty, forty, sixty, and seventy-five meter levels. Each truss station includes two thermocouples and thirty-two strain gauges (four on each of the eight truss members). Two x and y pairs of accelerometers are located at each station except the base station, where four triaxial accelerometers are used. Load cells are incorporated into the truss mounting structure at the four truss-to-Orbiter interface points. Optical targets (retroreflectors) are placed at numerous locations on the forward face of the truss.

SAVE
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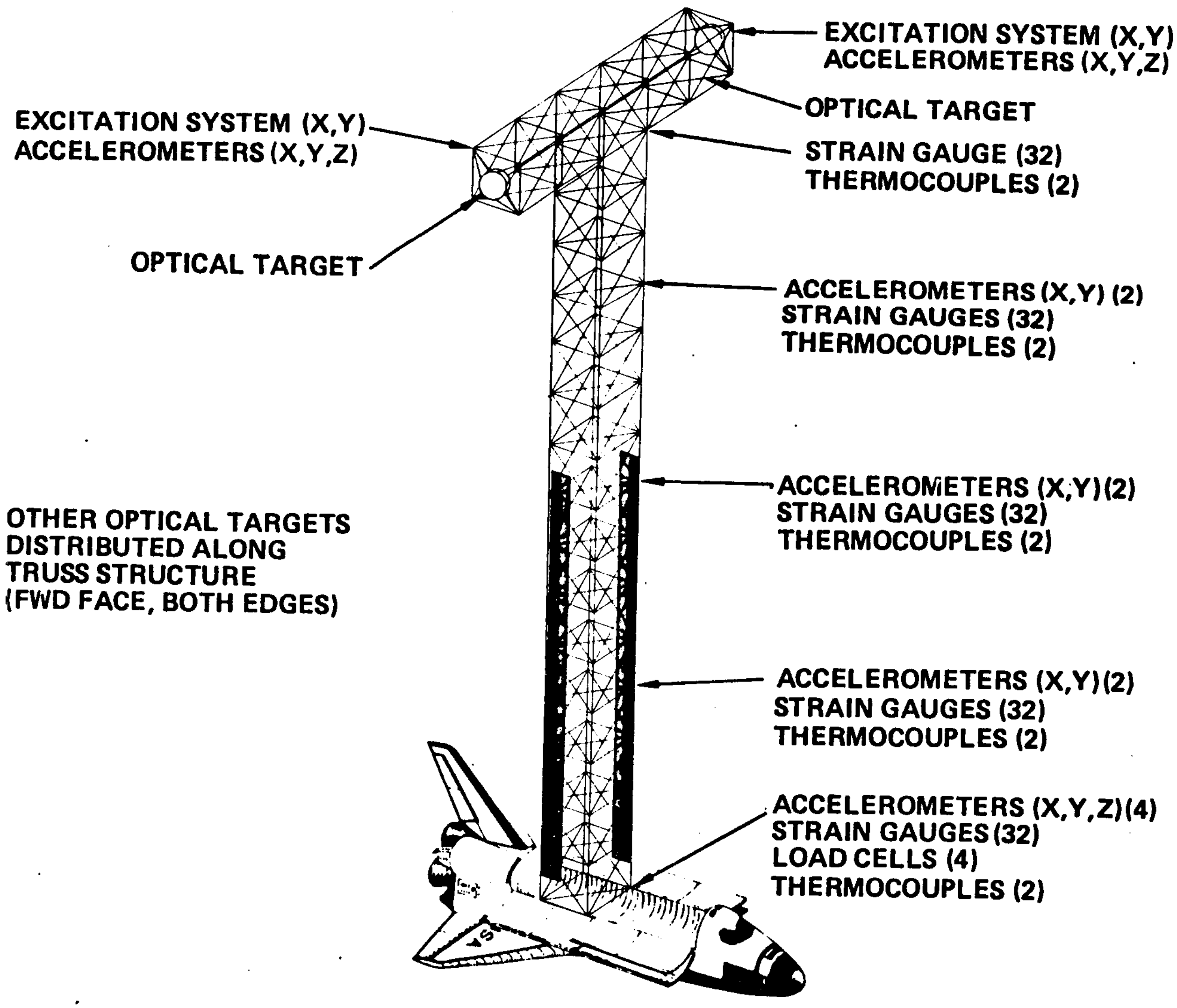
Structures and Assembly Verification Experiment (SAVE)

Test Instrumentation



VIBRATION EXCITATION SYSTEM

The basic force and frequency requirements for the excitation system are itemized along with candidate types of inertia shakers.

To achieve the desired truss loads, it is estimated that forces between zero and eighteen Newtons (four pounds) will be required, depending on the amount of damping that occurs in the truss structure. A frequency range of from one quarter to ten Hertz is required to cover the frequency range of the lowest truss modes. Force control is necessary to provide constant or predictable force levels during the frequency sweeps.

Two types of inertial shakers were considered for the test excitation system. Linear shakers apply forces in single axis directions while rotary shakers can be used to produce forces in all radial directions.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Vibration Excitation System

BOEING

- Requirements
  - Sinusoidal forces up to 17.8 N (4 pounds)
  - Frequency sweeps from 0.25 to 10 Hz.
  - Constant forces during the frequency sweeps
- Inertia type shakers
  - Forces in orthogonal directions
  - Forces in all radial directions

INERTIA SHAKER CANDIDATES

Linear motor shakers and rotary motor shakers were considered for use with the experiment.

Linear motor shakers require a mass of about four and one-half kg (ten pounds) and a linear stroke of up to two hundred and fifty-four mm (ten in.) in each direction to produce the required forces. The resulting power usage is approximately two hundred watts. These shakers are force servos and exhibit good force control.

Rotary motor shakers require less electrical power due to higher mechanical advantage obtained through gears. They rely on eccentrically weighted rotating wheels to produce centrifugal forces in all radial directions. A single axis shaker can be implemented by using two counter-rotating wheels. Since the forces are a function of rotational speed, this type of shaker is a velocity servo and exhibits poor force control.

Structures and Assembly Verification Experiment
(SAVE)

Inertia Shaker Candidates

- Linear motor shaker
  - Requires large amounts of electrical power (≈ 200 watts)
  - Weight movement up to ± 254 mm (± 10 inches)
  - Moving weight approximately 4.54 Kg (10 pounds)
  - Force servo
  - Good force control
- Rotary motor shaker
  - Requires less electrical power due to mechanical advantage
  - Eccentrically weighted rotating wheels
    - Counter-rotating wheels for translational forces
    - Single wheel for all direction radial forces
  - Velocity servo
  - Poor force control

INERTIA SHAKER

A rotary inertia shaker schematic is shown in this figure. The counter rotating wheels with eccentric masses produce a linear force that depends on the speed of rotation. Some degree of force compensation can be obtained by using spring-mass systems that tend to offset the eccentricity of the rotating system as rotational speeds increase.

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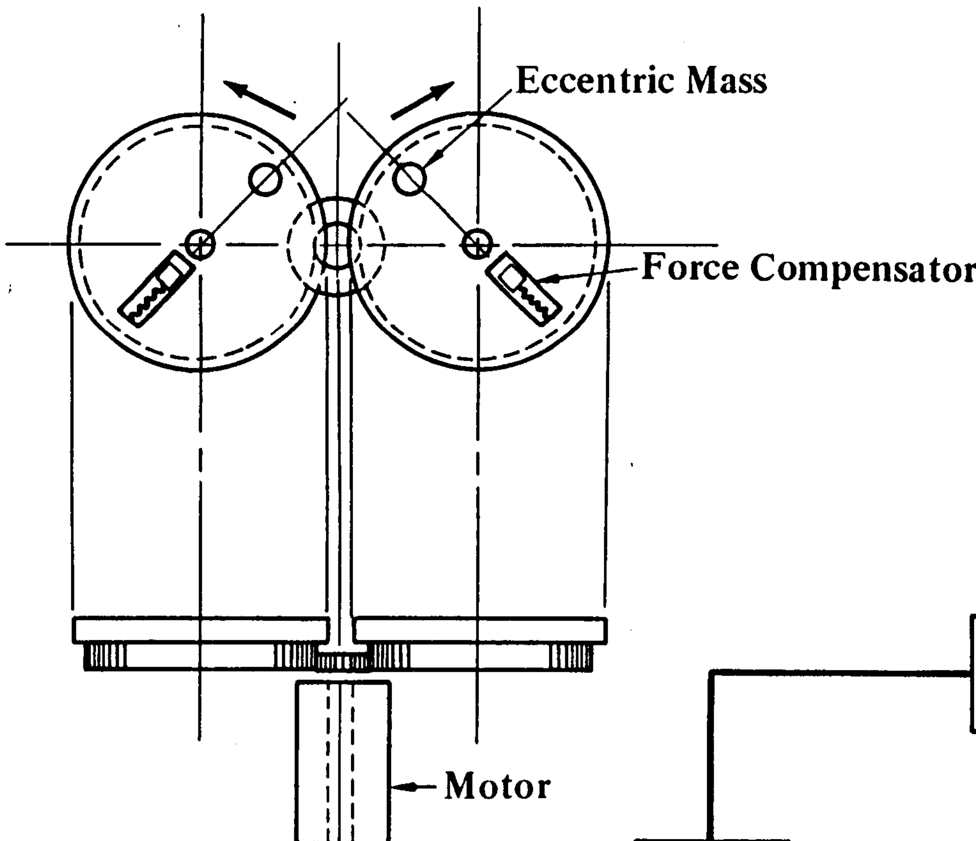
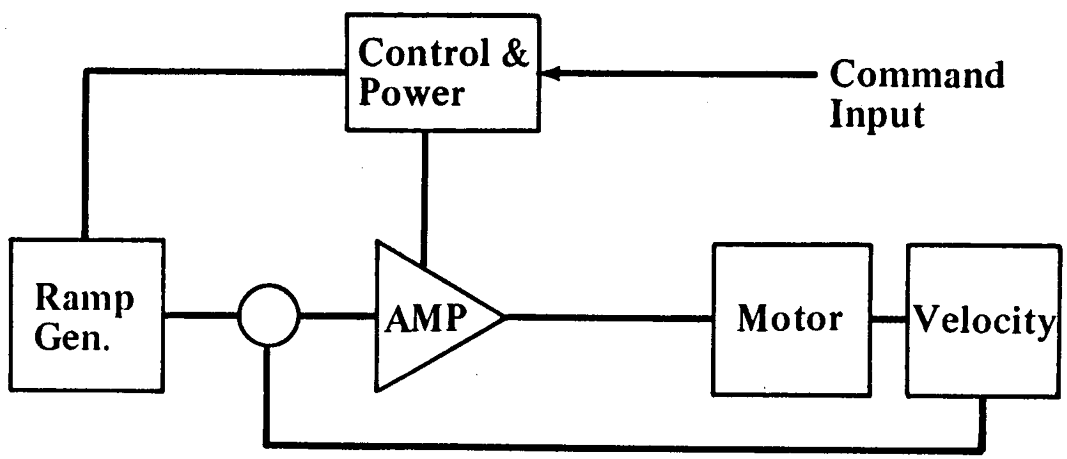
Structures and Assembly Verification Experiment (SAVE)

Inertia Shaker

BOEING





LINEAR MOTOR SHAKER

The shaker concept selected for the experiment is the linear motor shaker shown schematically in this figure. A moving armature (mass) is driven along a guide rod by a field coil (or permanent magnet if current is applied to the armature). This system uses acceleration feedback to control the applied forces.

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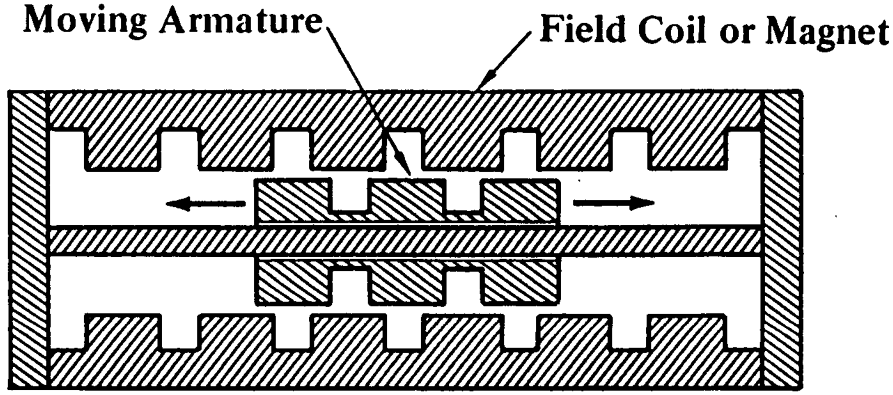
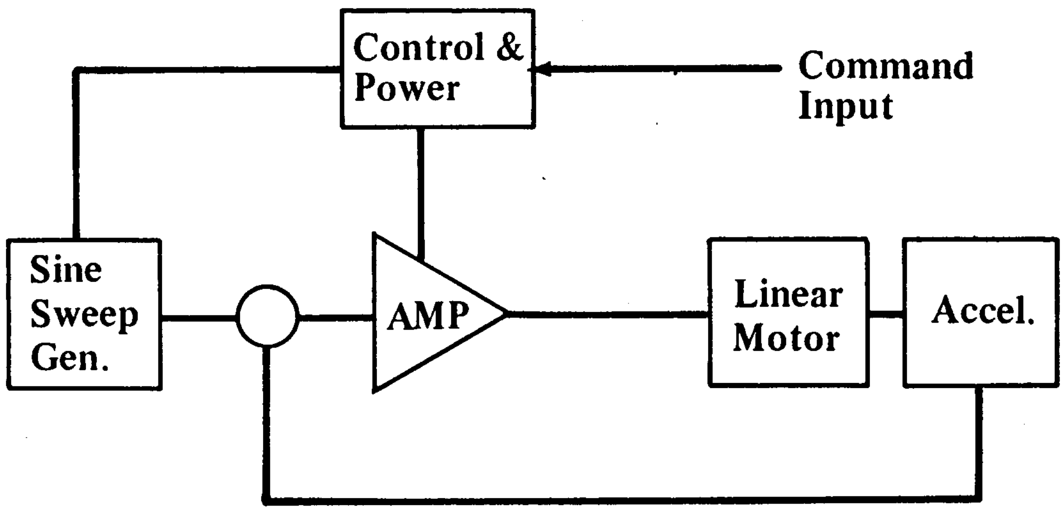
Structures and Assembly Verification Experiment (SAVE)

Linear Motor Shaker

BOEING

SELECTED CONCEPT





INSTRUMENTATION, ACCELEROMETERS

The next two charts compare the attributes of three types of accelerometers that are commonly used for dynamic testing: piezo-electric, piezo-resistive, and servo accelerometers.

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Structures and Assembly Verification Experiment (SAVE)

Instrumentation, Accelerometers

BOEING

- Piezo-electric accelerometers
    - Frequency range > 1.0 Hz.
    - Medium sensitivity, 0.01 to 1.0 volts per G.
    - Small dimension, 6.35mm (0.25 inches) O.D. minimum
    - Low mass, down to 1 gram (.002 lb)
    - Very rugged, high vibration (1000 G) and wide temperature
- Piezo-resistive accelerometers
    - Frequency range 0 to > 50 Hz.
    - Low sensitivity, .001 to .050 volts per G.
    - Small dimension, 6.35 to 25.4 mm (.25 x 1.0 inches) minimum
    - Low mass, down to 5 grams (.01 lb)
    - Rugged, vibration (200 G) and wide temperature

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Structures and Assembly Verification Experiment
(SAVE)

Instrumentation, Accelerometers (cont'd)

BOEING

- Servo accelerometers
  - Frequency range 0-100+Hz.
  - High sensitivity, 0.1 to 100 volts per G.
  - Relatively large, 25.4 mm (1.0 inch) cube minimum
  - Medium mass, down to 50 grams (0.11 lb)
  - Vibration (100G) from -33°C to 66°C (-27° to 150°F.) temperature

ACCELEROMETER ASSESSMENT

Servo accelerometers were selected because piezo-electric accelerometers do not adequately cover the range of frequencies of the experiment and piezo-resistive accelerometers lack the sensitivity required to measure the small accelerations expected.

Structures and Assembly Verification Experiment
(SAVE)

Accelerometer Assessment

BOEING

- Piezo—electric — Frequency range not low enough
- Piezo—resistive — Sensitivity too low
- Servo — Selected

INDIVIDUAL TRANSDUCER CABLE CONCEPT
TOWER BASE SIGNAL CONDITIONING

The simplest and most reliable of the three cable system candidates considered for the experiment uses separate, shielded, multi-wire cables for each transducer. Signal conditioning and recording is accomplished at the data system module in the Orbiter bay. This system, however, results in a very large cable bundle as more and more instrument leads are added. One hundred and fifty-seven transducers are located above the bottom of the truss.

SAVE
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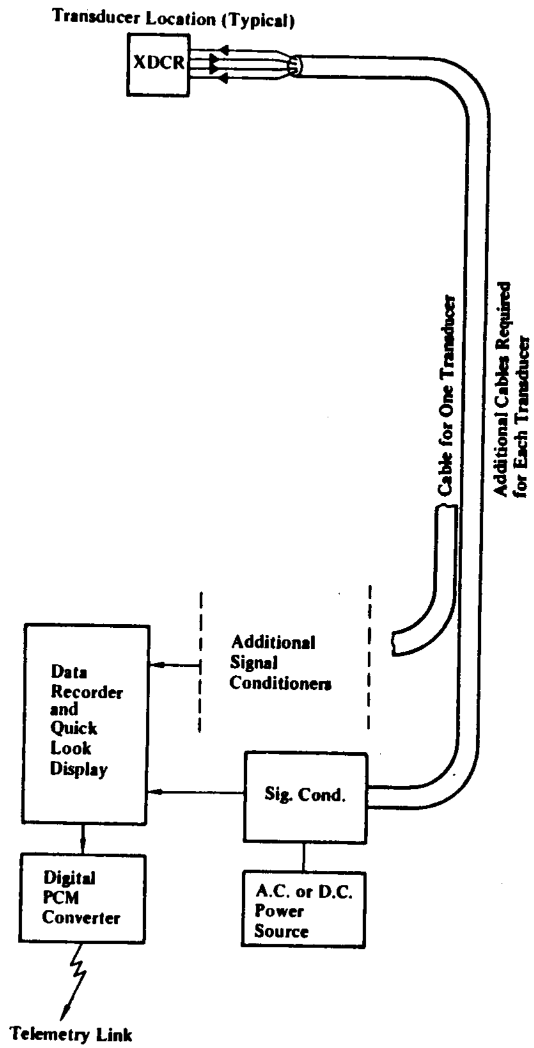
Structures and Assembly Verification Experiment (SAVE)

Individual Transducer Cable Concept, Tower Base Signal Conditioning



- Separate Cables
- Reliable
- Simplest
- Large Cable Bundles

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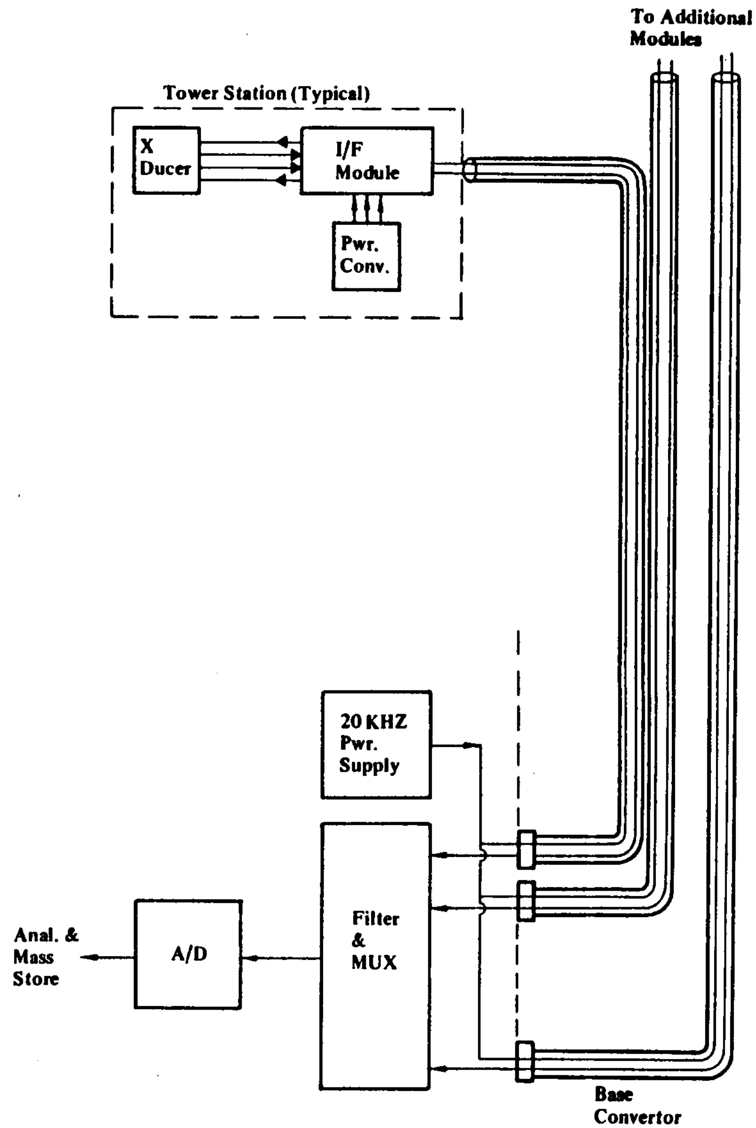
INDIVIDUAL BUS CONCEPT

The individual bus concept is similar to the previous concept in that each transducer has its own cable. By providing an interface module at the transducer location, the size of the individual cables are reduced to shielded, two-wire cables. The base converter processes the signals for display and recording. The size of the cable bundle at the base of the truss is smaller than the individual transducer cable concept, but is still large.

Structures and Assembly Verification Experiment (SAVE)

Individual Bus Concept



- Local Signal Conditioning
- Separate Cables
- Large Cable Bundles

COMMON BUS CONCEPT, TOWER STATION SIGNAL CONDITIONING

This concept utilizes a single cable loop (bus) which extends the full length of the truss. Each transducer incorporates local signal conditioning and a coupler which superimposes the data signal onto a carrier signal that is unique for each transducer. Each transducer signal is then fed into the common bus. The tower base system separates each signal from its carrier and prepares it for display and recording. This state-of-the-art system was selected for the experiment.

SAVE
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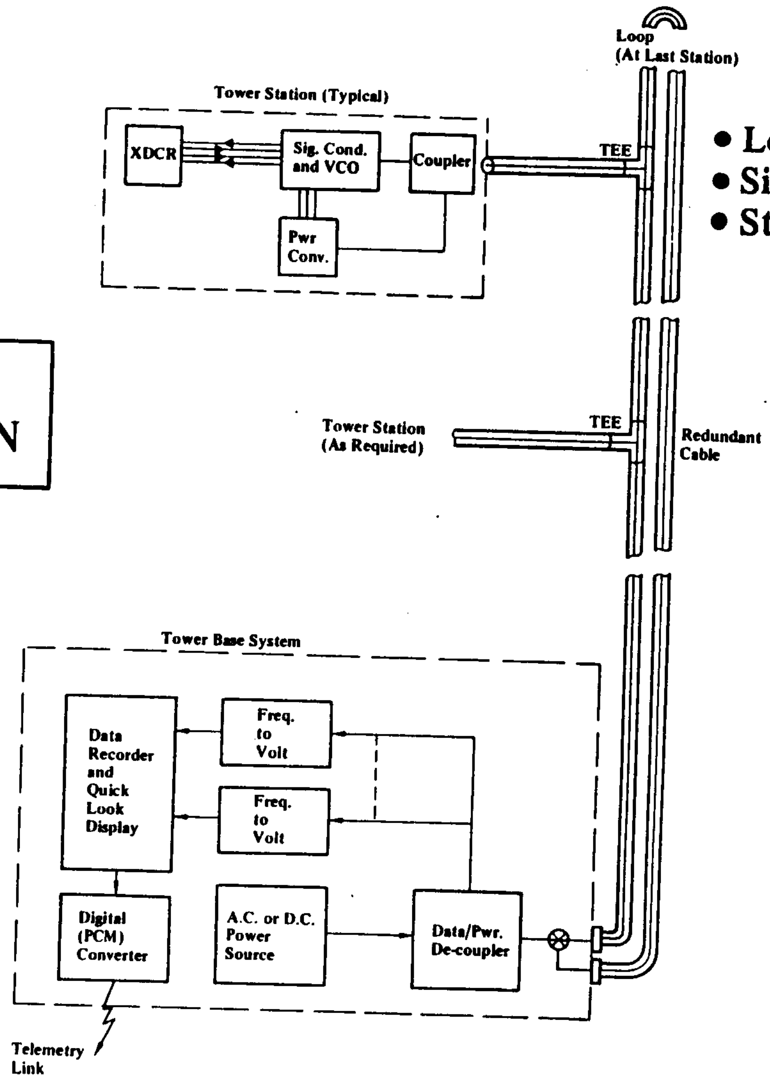
Structures and Assembly Verification Experiment (SAVE)

Common Bus Concept, Tower Station Signal Conditioning

BOEING



- Local Signal Conditioning
- Single Cable Loop
- State of The Art Technology

SELECTED CONFIGURATION

X 24442 ORIG 9/84

OPTICAL MEASUREMENT SYSTEMS

Optical systems are envisioned for both static measurements of the truss and for dynamic measurements. A photogrammetric system will be used for the static shape measurements while a laser optical system will measure displacements during dynamic tests.

Photogrammetric methods developed by Geodetic Services, Inc. (GSI) of Melbourne, FL are suggested for static measurement of the truss. This system uses several remotely operated, large format cameras to photograph light reflecting from retroreflector patches attached to many points on the structure. The light is supplied by ring strobes at the camera locations. The cameras are aligned prior to Orbiter launch and fixed in that position. The photographs are processed following return to earth and are analyzed by computers using sophisticated triangularization methods to determine the static shape of the truss.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Optical Measurement Systems

BOEING

- Static Shape - Photogrammetry Methods
  - GSI - Melbourne, Fla.
  - 9” x 9” Format Camera, 125 Exposures, 1 Frame/5 Sec.
  - Illuminating ring strobe at camera, retrotargets at measurement locations.
  - Canister and remote control not yet developed
  - Available data system and analysis package includes; software and IBM-PC.
- Dynamic tests - Laser beam optics

PHOTOGRAMMETRY MEASUREMENT PRECISION

Computer simulations of the SAVE truss and proposed camera locations were used by GSI to predict the precision attainable with the proposed system. Three camera locations were used for these simulations: two on the forward cargo bay bulkhead and one directly under the SAVE truss, looking along the truss axis. This table shows the expected measurement accuracy (1-sigma values) at three distances along the truss for three camera configurations. The poorest accuracy is obtained by postulating a failure of the truss base camera.

SAVE
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Structures and Assembly Verification Experiment
(SAVE)

Photogrammetry Measurement Precision

BOEING

Camera Configuration	Truss Level m (ft)	1—Sigma Accuracy, mm (in.)		
		X	Y	Z
Three cameras operational	10 (32.8)	0.2 (.008)	0.2 (.008)	0.4 (.016)
	40 (131)	0.4 (.016)	0.2 (.008)	1.4 (.06)
	80 (262)	0.6 (.02)	1.0 (.04)	5.0 (.20)
One bulkhead camera out	10 (32.8)	0.2 (.008)	0.2 (.008)	0.4 (.016)
	40 (131)	0.4 (.016)	0.2 (.008)	1.8 (.07)
	80 (262)	0.6 (.02)	1.2 (.05)	6.6 (.26)
Truss base camera out	10 (32.8)	1.8 (.07)	0.4 (.016)	1.4 (.06)
	40 (131)	3.4 (.13)	0.6 (.02)	7.8 (.31)
	80 (262)	6.2 (.24)	4.6 (.18)	28.6 (1.13)

LASER BEAM GEOMETRY

The laser measurement system utilizes a laser source located at the forward bulkhead of the Orbiter cargo bay and eight retroreflectors attached to the SAVE truss. The targets are located on both the port and starboard edges of the truss at the twenty, forty, and sixty meter levels, and at the extremities of the "T".

SAVE
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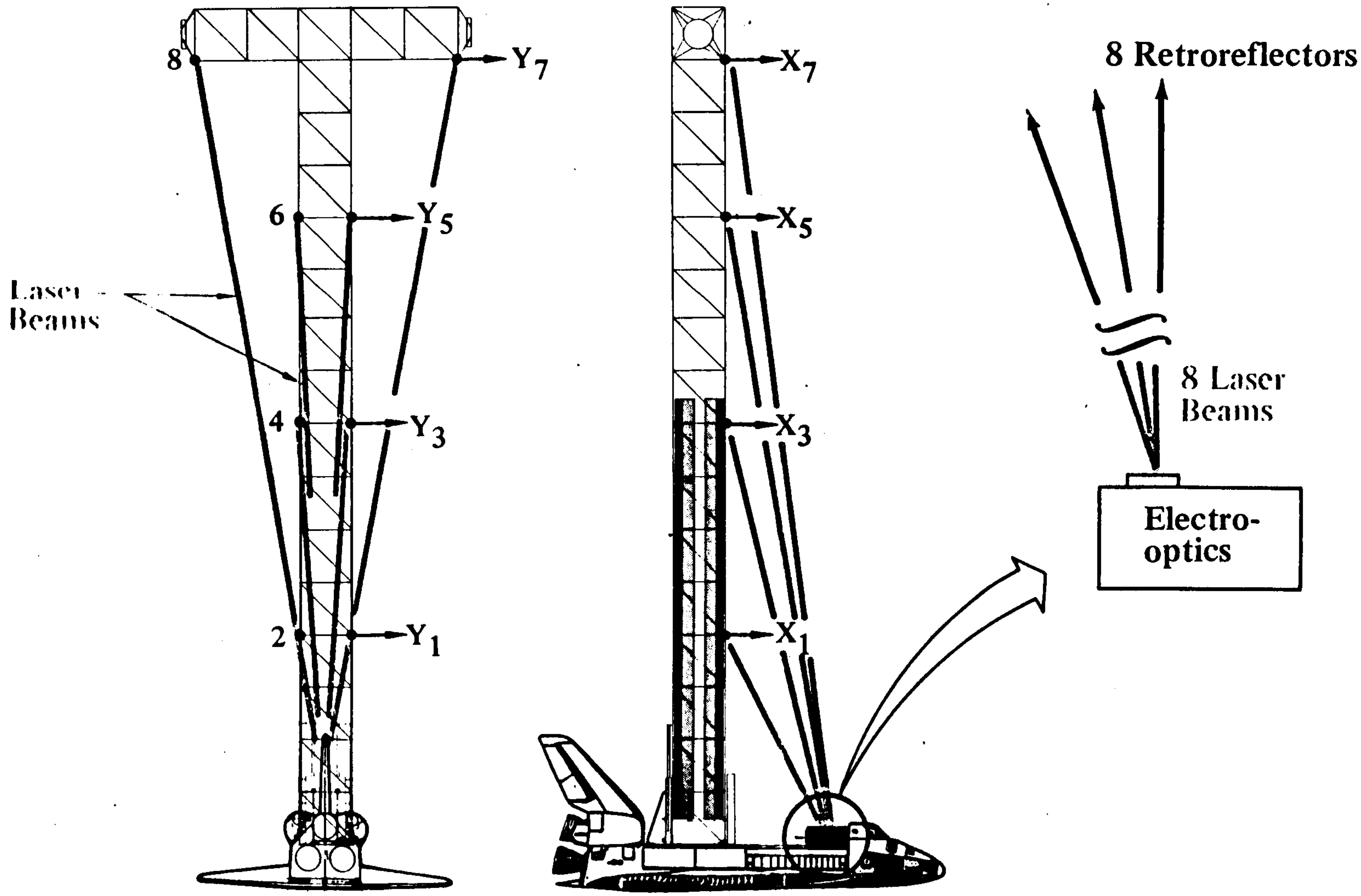
Structures and Assembly Verification Experiment (SAVE)
Laser Beam Geometry



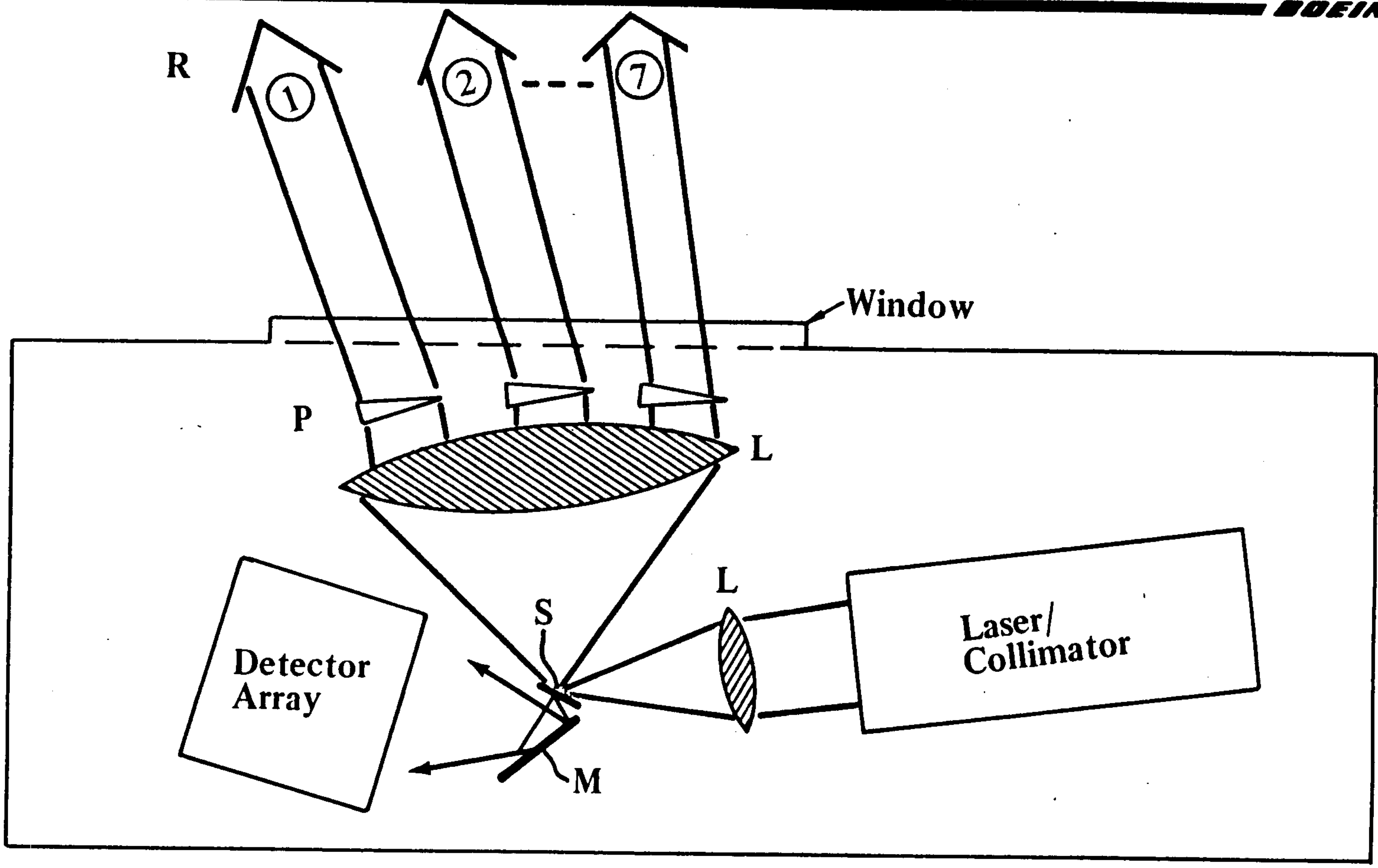
X-34443 ORIG 8/84

TWO-AXIS VIBRATION MEASUREMENT OPTICS

The functions of the laser measurement system are depicted in this schematic. A system of lenses, prisms, and a beam splitter aims the laser beam both toward the retroreflectors and toward the detector array. The detector compares the source signal with the reflected signal to measure dynamic structural deformations.

Structures and Assembly Verification Experiment (SAVE)

2-Axis Vibration Measurement Optics



R	Retroreflectors
L	Lens
M	Mirror
S	Beam Splitter
P	Prism

SAVE FREE FLYER SPACECRAFT BUS OPTIONS

Four free flyer bus options are considered. The first is a single bus, full-up system, requiring a full suite of earth and sun attitude sensors, a full-time attitude control system, and full-time flight operations monitoring. The second is a single bus utilizing gravity gradient attitude control the majority of the time and active attitude control with simplified sensors for short periods during reboost. Flight operations monitoring is required for pitch maneuvers prior to and following reboost and during reboost. Variations include: 1) addition of a momentum wheel to alter and/or increase stability of the gravity gradient stabilized attitude*, and 2) onboard or ground closure of active attitude control. The third bus option utilizes the same attitude control schemes as the second option and adds a second bus (split bus) with a second reboost thruster to eliminate the necessity of a pitch maneuver for reboost. The fourth option is a single bus with a very low thrust rebooster operating continuously. Gravity gradient is used full time for attitude control. The addition of a momentum wheel is a possible variant as above. Minimal command and control equipment and flight operations monitoring are required with this option.

*Gravity gradient attitude control without a wheel is denoted "passive" and control with a wheel is denoted "semi-passive".

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

SAVE Free Flyer Spacecraft Bus Options

BOEING

1. Full up, full time active attitude control
   Single bus high thrust reboost

2. Gravity gradient quiescent period attitude control
   Short term active attitude control for reboost
   Integrated sensors
   Single bus high thrust reboost

3. Gravity gradient quiescent period attitude control
   Short term active attitude control for reboost
   Integrated sensors
   Split bus high thrust reboost

4. Full time gravity gradient attitude control
   Very low thrust continuous reboost
   Minimal control, communications, command, and data

FULL TIME ACTIVE ATTITUDE CONTROL FREE FLYER CONFIGURATION - OPTION ONE

A single bus on the base of the SAVE truss (end opposite the cross "T") contains all of the attitude control, reboost, power, command and control, and communications equipment. Full time active attitude control allows quiescent (non-reboost) period flight at any attitude. The end-on orbit attitude, as shown in the figure, is selected to minimize drag, because undisturbed attitude control moments are minimized, and because no attitude change is required for reboost.

The full bus includes a control computer, sun and earth sensors, command and data handling equipment, six ten-Newton hydrazine RCS attitude control thrusters, one two hundred and twenty-two Newton reboost thruster, hydrazine tankage and control system, transponder, and power system.

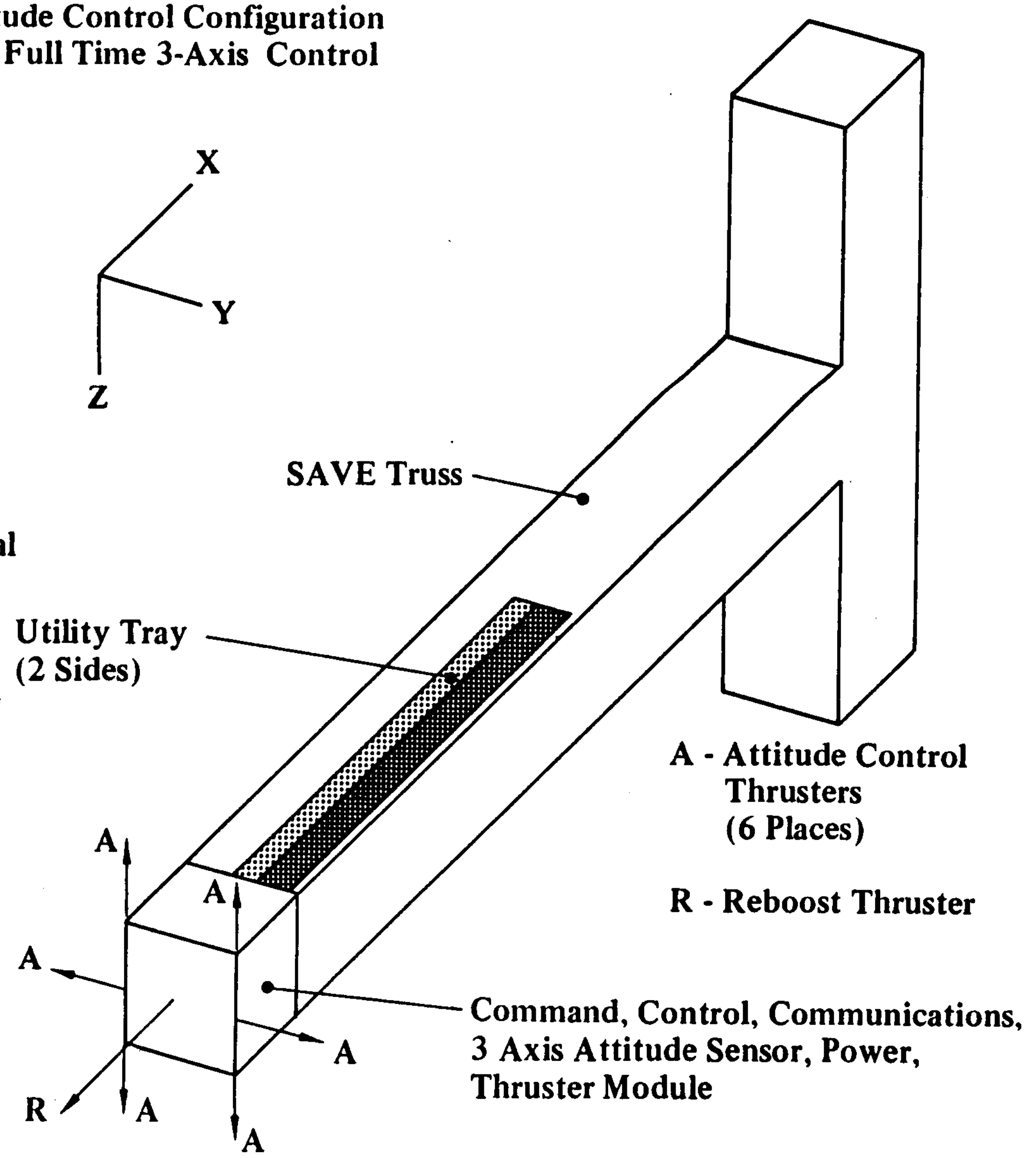
The attitude x control thrusters act in the y-z plane and the reboost thruster acts through the c.g. parallel to the long (x) axis of the truss as shown in the figure. Five Hohmann transfer reboosts over three years require about one and four-tenths million Newton seconds impulse using about six hundred and thirty Kg of fuel. Two reboost thruster burns of about ten minutes each for each orbit transfer provide the required impulse. The burn duration may be modified by ground control as required to maintain the orbit.

Structures and Assembly Verification Experiment (SAVE)

SAVE Orbit Maintenance

Active Attitude Control Configuration
Single Bus - Full Time 3-Axis Control

X-Z Orbit Plane
Z NADIR
X Velocity Direction
Y Negative Orbit Normal



X 24442 ORIG 9/84

ACTIVE REBOOST ATTITUDE CONTROL FREE FLYER CONFIGURATION - OPTION TWO

A single bus on the base of the SAVE truss contains a passive damper, a momentum wheel, attitude control, reboost, power, command and control, and communications equipment. Attitude control is by gravity gradient augmented by the momentum wheel during non-reboost quiescent periods. The wheel has three hundred and fifty Newton meter seconds angular momentum in the plane of the "T" and perpendicular to the long axis. The figure shows the truss in the gravity gradient stabilized face-on orbit attitude. The wheel momentum is in the direction of the orbit angular velocity (x).

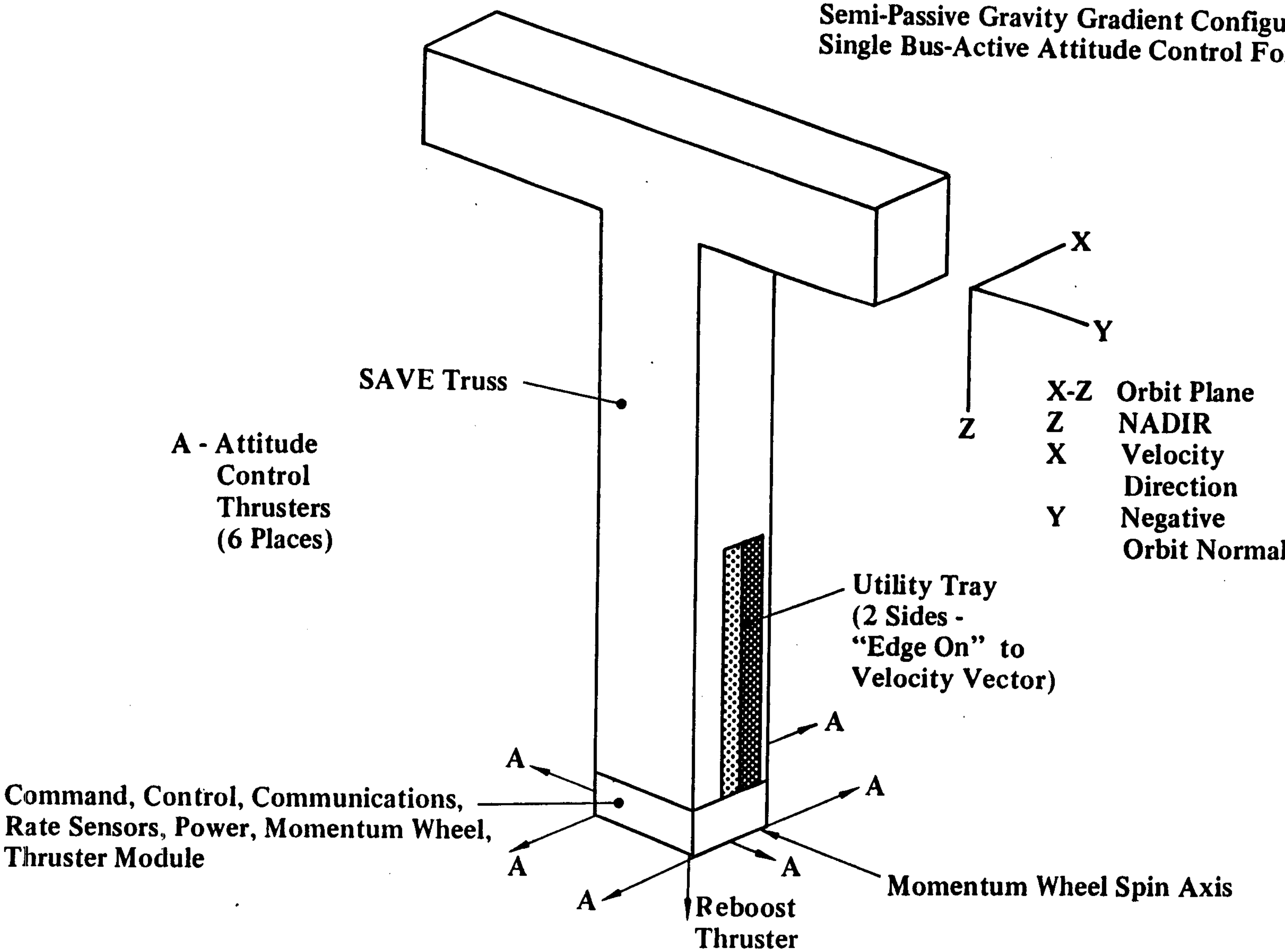
The active attitude control system of this configuration is much less complex than that of the full-time control configuration. The short term control is used only during reboost, allowing use of simple rate sensors and accelerometers with control loop closure through ground control. Only minimal flight operations monitoring is required between reboosts.

The attitude control system is ground activated for reboost. A ground command pitches the SAVE truss ninety degrees, holds that attitude during the reboost burn, and returns the truss to the quiescent nadir alignment following the reboost burn. The reboost and attitude control thrusters are as described for the preceeding option.

Structures and Assembly Verification Experiment (SAVE)

SAVE Orbit Maintenance

Semi-Passive Gravity Gradient Configuration
Single Bus-Active Attitude Control For Reboost



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ACTIVE REBOOST ATTITUDE CONTROL, SPLIT BUS FREE FLYER CONFIGURATION - OPTION THREE

A split bus is utilized to allow reboost without a pitch maneuver from the quiescent gravity gradient stabilized attitude. A bus at the base of the "T" contains a passive damper, a momentum wheel, four RCS attitude control thrusters for roll and yaw control, a single reboost thruster oriented normal to the plane of the "T", power, command and control, and communications equipment. A bus at the top of the "T" contains a single reboost thruster similarly oriented, as shown in the figure. The thrust level of the two reboost thrusters is balanced to produce minimum pitch moment when both thrusters are operating.

Attitude control is similar to that for the single bus configuration except that active pitch control is achieved by on-off control of the individual reboost thrusters.

This configuration provided no cost saving and added complexity to the assembly procedure. The split bus may also compromise the SAVE dynamic tests.

SAVE
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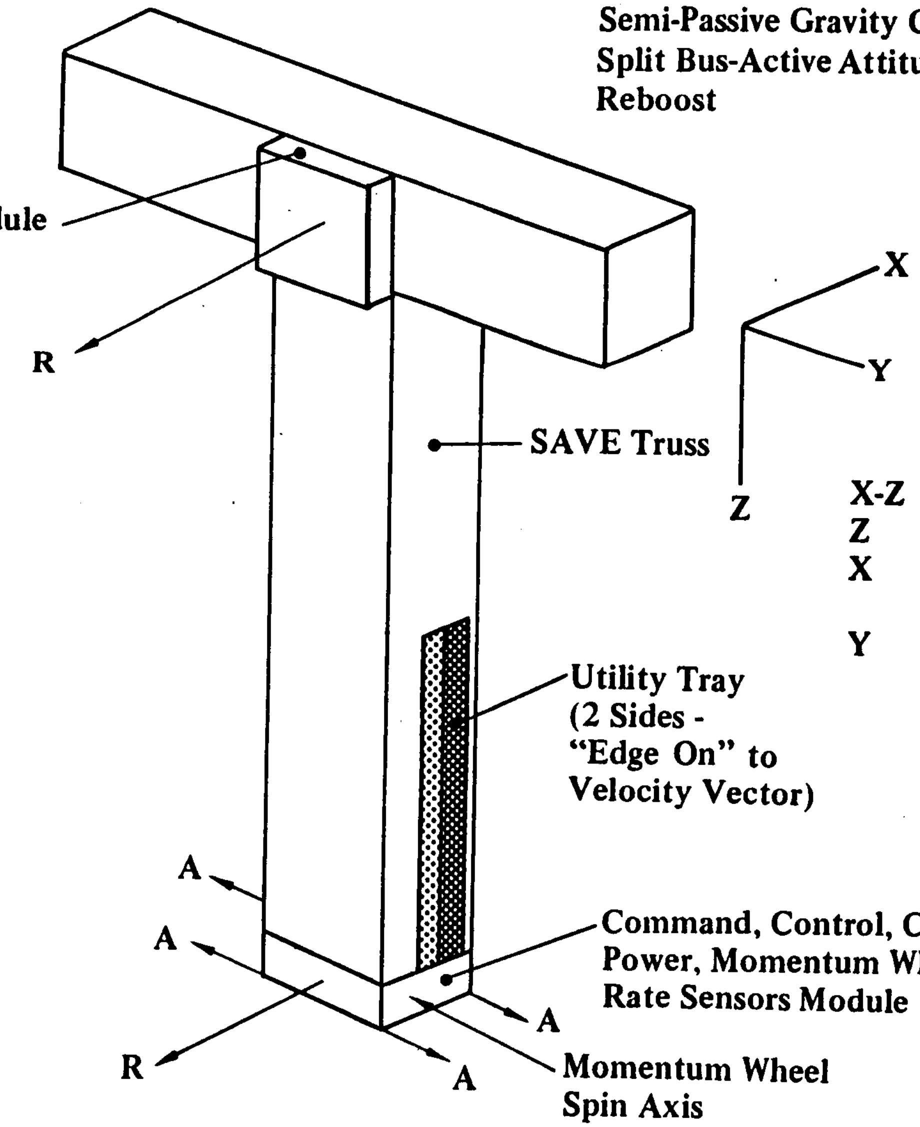
Structures and Assembly Verification Experiment (SAVE)

SAVE Orbit Maintenance

Semi-Passive Gravity Gradient Configuration
Split Bus-Active Attitude Control For Reboost



R-Reboost and Pitch Control Thrusters (2 Places)

A-Roll/Yaw Attitude Control Thrusters (4 Places)

X-Z	Orbit Plane
Z	NADIR
X	Velocity Direction
Y	Negative Orbit Normal

X 24442 ORIG 9/84

PASSIVE GRAVITY GRADIENT ATTITUDE CONTROL FREE FLYER CONFIGURATION - OPTION FOUR

A single bus on the base of the SAVE truss contains a passive damper, the reboost thruster, power, command and control, and communications equipment. Attitude control is by passive gravity gradient only, resulting in an edge-on stable orbit attitude, as shown in the figure. This configuration is stable with either edge forward and either the base or top of the "T" toward the nadir.

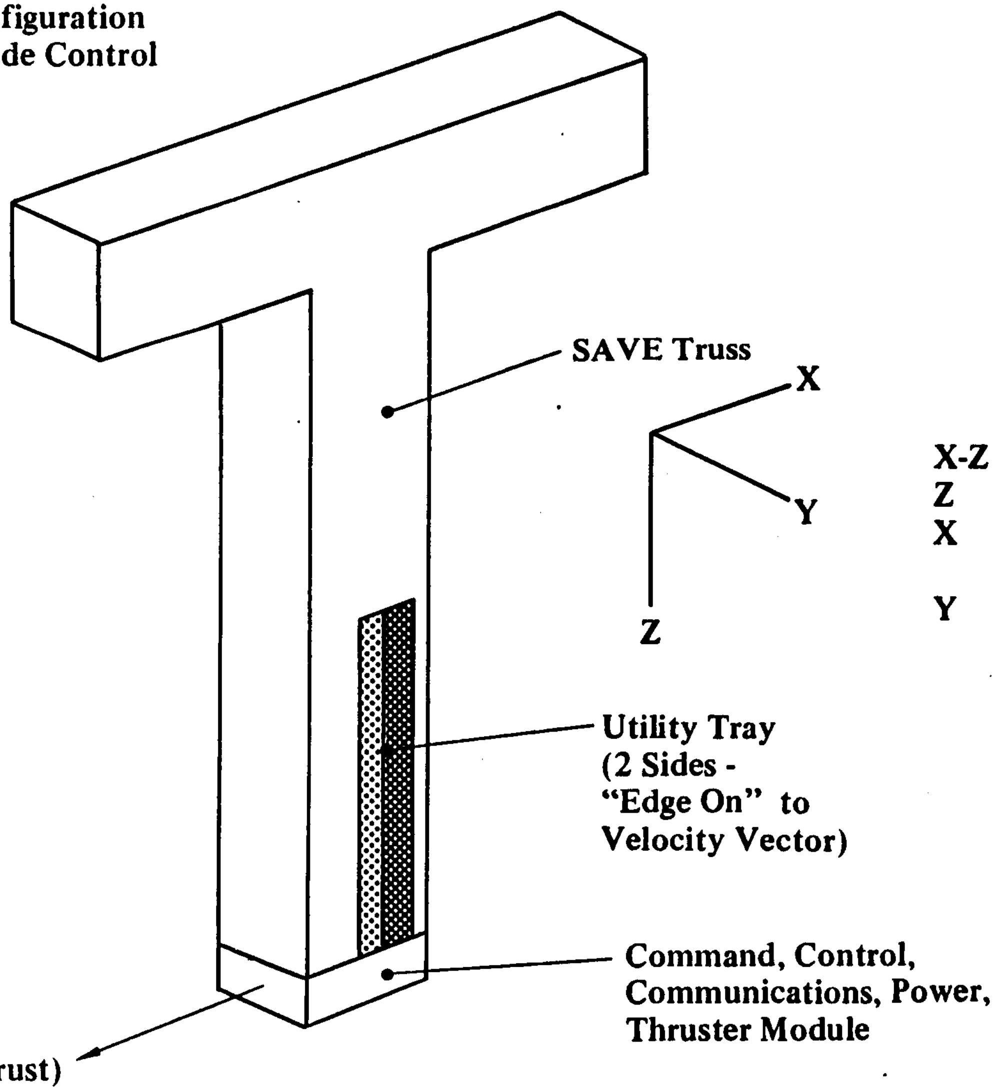
The utility trays are mounted on the face of the "T" truss (not the nominal configuration) to achieve an "edge-on" attitude for the trays themselves. The drag of the utility trays "face-on" is so large as to be considered totally impractical. This fully passive control configuration is presented to show the off nominal tray installation it requires.

Reboost thrust is continuous at about one one-hundredth Newtons (three one-thousandths pounds) adjusted by ground command as required. Gravity gradient is adequate to maintain "edge-on" attitude control with the very low continuous reboost thrust.

Structures and Assembly Verification Experiment (SAVE)

SAVE Orbit Maintenance

Passive Gravity Gradient Configuration
Single Bus - No Active Attitude Control



X-Z	Orbit Plane
Z	NADIR
X	Velocity Direction
Y	Negative Orbit Normal

SEMI-PASSIVE GRAVITY GRADIENT ATTITUDE CONTROL FREE FLYER CONFIGURATION - OPTION FOUR WITH MOMENTUM WHEEL

A single bus on the base of the SAVE truss contains a passive damper, a momentum wheel, reboost thruster, power, command and control, and communications equipment. Attitude control is by gravity gradient augmented by the momentum wheel. Semi-passive gravity gradient control produces a "face-on" stable orbit attitude as shown in the figure. This configuration, with the wheel, is stable with either the base or top of the "T" toward the nadir, but only with the wheel angular momentum in the direction of the orbit normal.

Reboost thrust is continuous and at the same level as for option four, adjusted by ground command as required to maintain the orbit. An ION thruster is utilized for this low thrust level. An alternative reboost system uses a four tenths Newton hydrazine thruster operating about three percent of the time. Gravity gradient augmented by a three hundred and fifty Newton meter second momentum wheel is adequate to maintain "face-on" attitude control with the very low continous reboost thrust.

The absence of an active attitude control system and discrete reboosts minimizes the requirements for command and data handling equipment and flight operation monitoring.

SAVE
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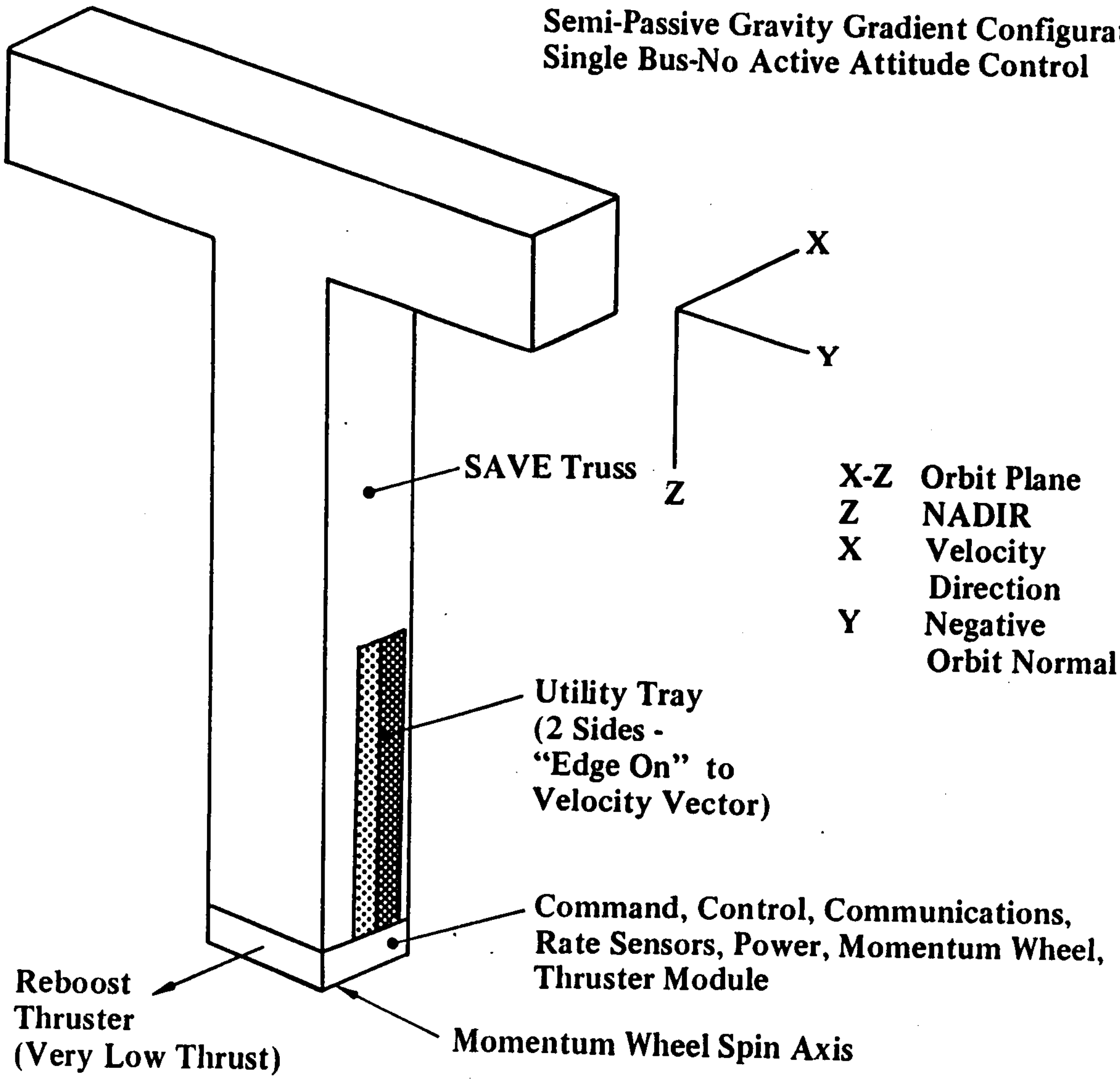
Structures and Assembly Verification Experiment (SAVE)

SAVE Orbit Maintenance

BOEING

Semi-Passive Gravity Gradient Configuration
Single Bus-No Active Attitude Control



SAVE FREE FLYER CONFIGURATION AND COST SUMMARY

The configurations and estimated total costs of the four free flyer bus options considered are shown in the table. The variations of ground or onboard control loop closure for the part time (reboost period) active attitude control are included. Also included are variations for gravity gradient attitude control with and without the momentum wheel. Note that the configurations without the momentum wheel, while costing less, require an off-nominal construction procedure to align the utility trays for acceptable drag. The split bus configuration also requires an off-nominal construction procedure to install the upper reboost bus.

The cost estimates are based on Boeing experience from similar programs.

SAVE
0046

Structures and Assembly Verification Experiment (SAVE)

Save Free Flyer Configurations and Cost Summary

BOEING

Reboost Attitude Control / Quiescent Attitude Control	Active - 3 Axis Full Sensors	3 Axis Rate Sensors Only				Gravity Gradient	Free Flyer Flight Configuration
	Single Bus (High thrust reboost)	Single Bus (High thrust reboost)		Split Bus (High thrust reboost)		Single Bus (Very low thrust continuous reboost)	
	On Board Control	Ground Control	On Board Control	Ground Control	On Board Control	Ground Control	
Full Time 3 Axis Control	$41M	–	–	–	–	–	End On (T FWD)
Semi Passive Gravity Gradient W Momentum Wheel	–	$25M **	$26M	$25M	$26M	$15M *	Face On
Passive Gravity Gradient W/O Momentum Wheel	–	$24M	$25M	$24M	$26M	$14M	Edge On

* Recommended Configuration
** Optional Recommended Lower Risk Configuration

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SAVE FREE FLYER COST BREAKDOWN

The cost breakdown for the four options and their variations is shown in the table. Utilization of gravity gradient attitude control during quiescent periods, as opposed to full time active attitude control, has the greatest impact on cost reduction. Further reduction is achieved by going to full time gravity gradient attitude control, primarily by reducing command and data handling and system integration costs.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

SAVE Free Flyer Costs ($M)

BOEING

	3 Axis Full Time Attitude Control	Quiescent Gravity Gradient Attitude Control. 3 Axis Attitude Control During Reboost.				Full Time Gravity Gradient Control. Continuous Very Low Thrust Reboost
		Single Bus		Split Bus		
		Ground Control	On Board Control	Ground Control	On Board Control	
Control Computer Sensors Passive Damper Control Analysis	16	4	5	4	5	1
Propulsion	6	6	6	6	6	5
Power System	6	5	5	5	5	5
Command and Data Handling	6	4	4	4	4	1
Flight Operations	3	2	2	2	2	1
System Integration	4	3	3	3	3	1
Total W/O Wheel	$41M	24	25	24	25	14
Momentum Wheel for Face On		1	1	1	1	1
Total W. Wheel		$25M	$26M	$25M	$26M	$15M

SAVE FREE FLYER IMPACT ON CONSTRUCTION

The large surface area of the utility trays requires a free flyer orbit attitude that places the trays "edge-on" in the orbit plane to minimize drag and thus minimize orbit decay. The baseline SAVE truss assembly has the utility trays mounted on the side of the "T" (inside the truss). A "face-on" orbit attitude of the baseline "T" puts the trays in the minimum drag attitude. Gravity gradient attitude control requires a momentum wheel to achieve this attitude. A one million dollar cost for the momentum wheel is shown in the figure.

The alternative is to mount the trays on the face of the "T" and allow "edge-on" free flyer orbit attitude without the momentum wheel. Tray face mounting requires extra assembly time and complexity to rotate the first day's EVA construction prior to tray installation during the second days's EVA. The alternate construction will also adversely affect optical measurements during structural tests. The baseline approach was retained for the study.

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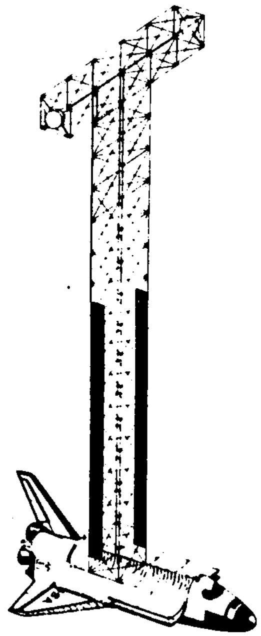
SAVE 0056

Structures and Assembly Verification Experiment (SAVE)

Experiment Construction Approach

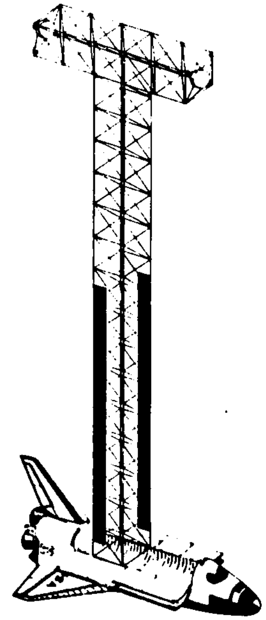
BOEING

Baseline



- Free Flyer Bus Cost $15M
- Construction Timelines = Baseline

Alternate



- Free Flyer Bus Cost $14M
- Construction Timeline = Baseline + 4 Minutes
- Some Reduction in Measurement Fidelity
  - Laser Optics - Dynamic Deflections
  - Photogrammetry - As - Built Configuration

X 24442 ORIG 9/84

SAVE FREE FLYER RECOMMENDED CONFIGURATION

The option four configuration with a momentum wheel is the recommended free flyer configuration. This is the least complex and least expensive configuration with a momentum wheel. Inclusion of the momentum wheel is strongly recommended to allow use of the baseline construction configuration and allow increased attitude stability.

While there are no flight rated ION propulsion systems available at this time, considerable ION engine development is underway. A pulsed low thrust hydrazine system is a viable alternative. Dynamic effects of pulsing should be of no consequence if pulsing frequencies are selected between the widely separated low frequency orbital dynamics and relatively high frequency structural dynamics.

Inversion from a correct initial stable orbit attitude is highly unlikely as it could only be caused by a large external disturbance. If inversion did occur, this configuration is not capable of rerighting from an inverted stable attitude.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)
SAVE Free Flyer Recommended Configuration

BOEING

- Features
  - Single bus at end of truss opposite "T"
  - Full time semi-passive gravity gradient attitude control
  - Momentum wheel for face on free flyer stability
  - Passive damper
  - Continuous very low thrust reboost ~0.013N (~ 0.003 lbs) average
    - ION propulsion
    - Pulsed low thrust hydrazine
  - Low cost ($15M)
- Risks
  - ION propulsion systems not flight certified
  - Pulsed hydrazine propulsion may introduce undesirable dynamics
  - No capability to pitch from undesirable stable orientation

SAVE FREE FLYER ALTERNATE RECOMMENDED CONFIGURATION

The option two configuration with a momentum wheel and ground closure of the part time active attitude control is an alternate free flyer recommendation. This configuration is recommended primarily as a higher cost and more complex backup to the option four configuration if the very low thrust continuous reboost system does not prove feasible.

This configuration has the capability of rerighting from a stable inverted attitude.

SPACE STATION

SAVE 0053

Structures and Assembly Verification Experiment (SAVE)

SAVE Free Flyer Alternate Recommended Configuration

BOEING

- Features
  - Single bus at end of truss opposite "T"
  - Quiescent semi-passive gravity gradient attitude control
  - Momentum wheel for face on free flyer stability
  - Passive damper
  - 3-axis active attitude control during reboost (hydrazine RCS)
  - Rate sensors for active attitude control
  - Control loop closure through ground control
  - High reboost thrust ~222N (~ 50 lbs)
  - Most hardware flight proven
  - Capability to pitch from undesired stable orientation
- Disadvantage
  - Higher cost ($25M vs. $15M)

X 24442 ORIG 9/84

FOLLOW-ON EXPERIMENTS

The SAVE program study postulates a free flyer spacecraft with appropriate controls and reboost capability to maintain orbit for three years. The free flyer affords a platform for further experiments which may be essential to Space Station technology development or of interest to the scientific community. The free flyer may be revisited on subsequent Orbiter flights for installation, evaluation, repair, or removal of experiments.

Several Space Station technology development experiments were evaluated to determine, on a preliminary basis, some of the more critical requirements for support of the experiment. The experiments are listed on the facing page, and discussed on the following three pages.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Follow-on Experiments

BOEING

Candidates

- Solar Dynamic Power System
- Rotary Fluid Coupling
- Truss Construction

SOLAR DYNAMIC POWER SYSTEM

A self-contained solar thermal-to-electric power generating system is being considered for Space Station. The system consists of a solar concentrating dish, a cavity receiver to convert concentrated solar energy to a heated, pressurized fluid, and a heat engine that converts thermal energy to electrical energy. When operational, the system provides its own electrical power and thermal control. There are additional requirements for start-up of the system. Power is required to heat the thermal storage medium and the heat transfer fluid to initial operating conditions. Power is also required for gimbal drives to point the system towards the sun. An electrical load will be necessary which may consist of resistive load banks and radiators. This device will require a means of control. A data acquisition and telemetry package will be necessary to collect, synthesize, and transmit performance information.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Follow-on Experiments

BOEING

Free Flyer

Proposed Experiment	Requirements
	• Start Up Power ≈ 3 KW • Heat Transfer Fluid • Thermal Energy Storage • Slew Drive
• 25 KW Solar Dynamic Power System • Dish Concentrator • Solar Receiver • Power Conversion System	• Data Acquisition and Telemetry Package • Temperature, Pressure • Power Characteristics • Position • Electrical Load Control • Operating Power and Thermal Control Provided by Experiment.

THERMAL CONTROL FLOW SYSTEM

The Space Station thermal control system contains elements of a two-phase flow system that may require demonstration and characterization in a zero-G environment. The elements of the system are a rotary fluid coupling, a pump, condenser, and evaporator. The coupling requires an actuator for drive. The fluid is ammonia and is divided into its two phases as it passes through the coupling. A leakage reservoir is provided with a heater that requires power to maintain a fifteen and one-half degrees Centigrade (sixty degrees F) temperature. Additional thermal control could be provided with selective coatings and multilayer insulation. A data acquisition and telemetry package will be necessary to collect, synthesize, and transmit performance information.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Follow-on Experiments

BOEING

Free Flyer

Proposed Experiment	Requirements
• Station Thermal Control Flow System • Rotary Fluid Coupling • Condensor • Evaporator • Pump • Piping	• Actuator Drive • Power ≈ 407 Joules (300 ft lb) Torque • Fluid Source - Ammonia • Fluid Pressure Source - 1 MPa (150 psi) • Leakage Reservoir Heater Power ≈ 35W • Passive Thermal Control - MLI Blanket • Data Acquisition and Telemetry Package • Torque Load Cell Output • Temperature, Pressure • Rotation Position (Encoder) • Leakage Rate

TRUSS CONSTRUCTION

The free flyer structure provides the basis for further in-space construction investigations provided the assembly fixture is designed as a construction aid and is left on-orbit with the truss. On a Shuttle return visit with the necessary components, it is possible to conduct tests representing construction of the Space Station truss following flight two. Revisiting the structure after a prolonged period on-orbit offers the opportunity to assess possible damage by meteoroids or debris and atomic oxygen. Also, there is the opportunity to investigate disassembly and repair techniques.

Power is required for the drive systems on the assembly fixture. The value shown on the figure represents a peak requirement when both the astronaut positioner system and truss translation (kicker) drive operate simultaneously. Individually the power requirements are: astronaut positioner, one and three-tenths kilowatts; rotation for stowage, one kilowatt; and truss translation drive, seven and one-tenth kilowatts. The latter requirement was sized for translating the entire experiment weight over a twenty-five second period. Power management could be applied to reduce the load. For instance, separate rather than simultaneous operation of systems, and faster truss translation during early construction stages with proportionately slower motion as the weight increases. The net effect would not change timelines.

Active thermal control is required for motors, communications elements, and computer control systems. Heaters are expected as well as passive thermal control coatings and multilayer insulation. Heater power requirements were not assessed.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Follow-on Experiments

BOEING

Free Flyer

Proposed Experiment	Requirements

• Truss Construction With Assembly Fixture	• Drive Power ≈ 8.4 KW
	• Heater Power TBD
	• Thermal Control
	  • Motors-Heater and Coatings
	  • Communications-Heater, Coatings and MLI
	  • Control System-Heater, Coatings and MLI
	• EVA Friendly
	• Additional Nodes and Struts

SCHEDULE ASSUMPTIONS

The SAVE program schedule assumes that designs of truss structure, utility trays, and the assembly fixture are completed by the Space Station program in time to support the SAVE program milestones. The schedule was developed using these guidelines: (1) the SAVE flight test results should be available substantially before the first Space Station flight to incorporate lessons learned; (2) Eastern Launch Site operations require about six months and the Orbiter/experiment integrated analysis must be completed prior to that activity; and (3) the Orbiter/experiment integrated analysis requires one year and starts after the design is frozen.

Structures and Assembly Verification Experiment
(SAVE)

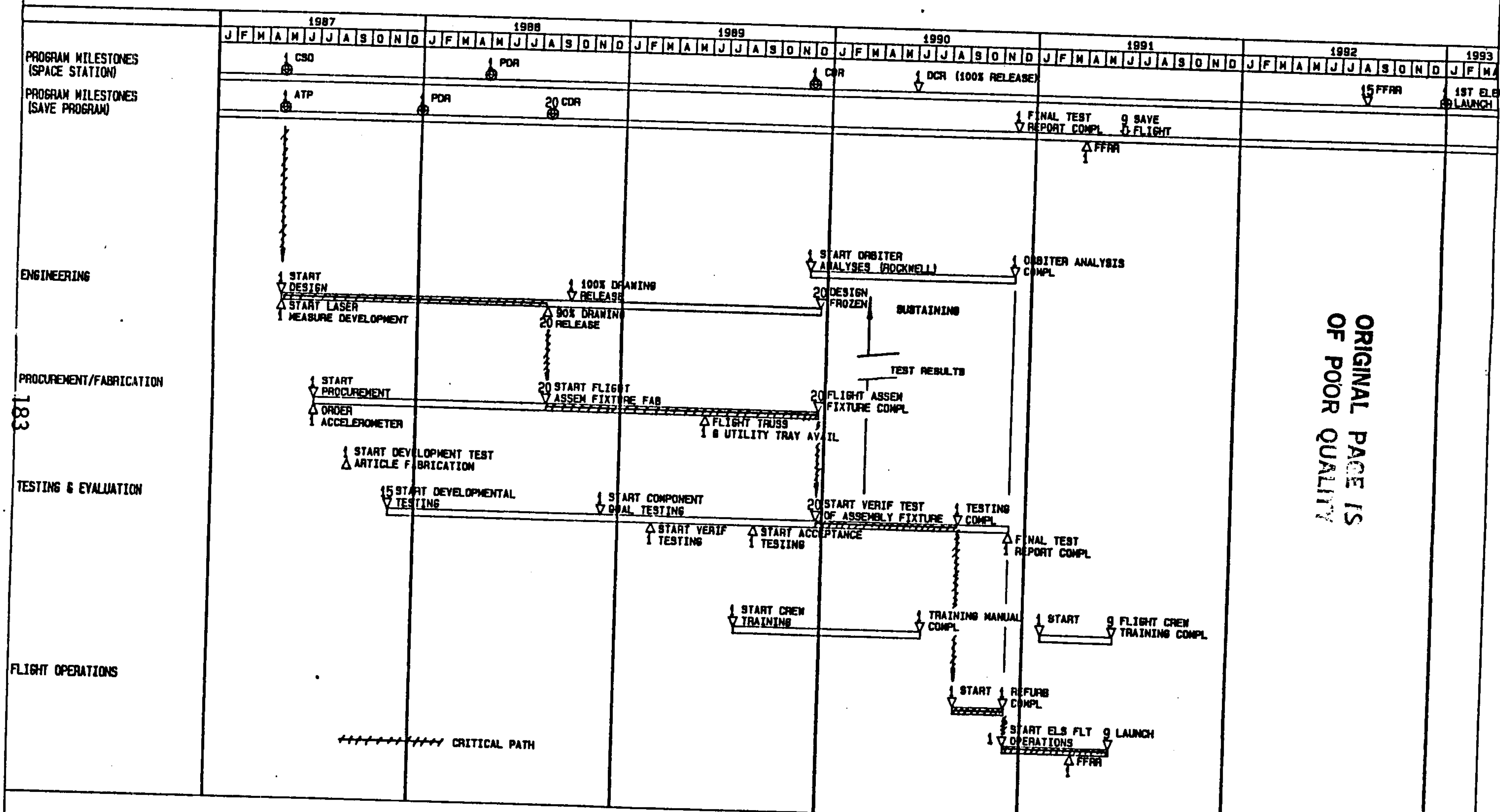
Schedule Assumptions

- Designs completed by Space Station program in time to support experiment.
- Experiment flight test results available substantially before first SS launch
- Orbiter integrated analysis requires 12 months and is complete at start of ELS flight operations.
- Detail parts fabrication starts before CDR.

MASTER PHASING SCHEDULE

Authorization to proceed on the SAVE program is coincident with the contract start date for Space Station Phase C/D. The critical path is the design development, fabrication, and testing of the assembly fixture. Verification testing of the assembly fixture is achieved early enough to provide experimental data for inclusion in the integrated Orbiter/experiment model and analyses by Rockwell. Substantial analyses during design development (1987-1988) will be required to assure that no major design deficiencies are found during the orbiter integrated analyses, when there is limited schedule recovery time. A period of three months has been allocated for refurbishment of the protoflight equipment prior to the start of Eastern Launch Site (ELS) integration. The SAVE flight date is June 9, 1991, approximately eighteen months before the first Space Station flight.

STRUCTURES & ASSEMBLY VERIFICATION EXP.
(SAVE)
MASTER PHASING SCHEDULE



PREPARED BY T.S. PPGC

SCHEDULE CONCLUSIONS

A success oriented schedule that starts at the same time as the Space Station Phase C/D contract will provide flight test results eighteen months before the first Space Station flight. This allows time to incorporate procedural changes and lessons learned into the Space Station flight training program. Fabrication of the experiment equipment in time to support testing requires release of designs for the assembly fixture, truss, and utility trays soon after the Space Station Preliminary Design Review. this necessitates an accelerated schedule for the Phase C/D contractor and introduces the risk of design changes after experiment fabrication has begun. There are no critical long lead purchases, however, development of the laser measurement system should be started at ATP.

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Program Schedule Conclusions

BOEING

- Success oriented - limited recovery time
- Element designs required before SS CDR
- No critical long lead purchases
- Substantial initial analysis required

PCM ESTIMATING METHOD

The Parametric Cost Model (PCM) is a collection of cost estimating relationships and factors that have been developed from Boeing's historical data. These relationships require hardware physical descriptions and programmatic data for inputs.

The primary hardware related inputs include classification of an item, weight, complexity, quantity, learning curve, and consideration of using existing designs. The primary programmatic inputs are wrap rates, complexity of functional support (SE&I, software, system test), schedule variation, level of tooling, and Class I changes.

For each hardware item, PCM generates manhour estimates for design, developmental shop, basic factory labor, and quality control; and it generates dollar estimates for these categories based on the wrap rates used. PCM also produces manhour and dollar estimates for hardware final assembly and checkout, SE&I, software engineering, system ground test, support equipment design and manufacturing, tooling, special test equipment, spares, liaison engineering, data, program management, and schedule penalty. Wraparound rates convert labor and material estimates to costs. Vendor estimates and discrete costs for certain given items can be input directly into the model for summation. The model will provide lump sum costs and will spread costs as a function of schedule time.

SAVE
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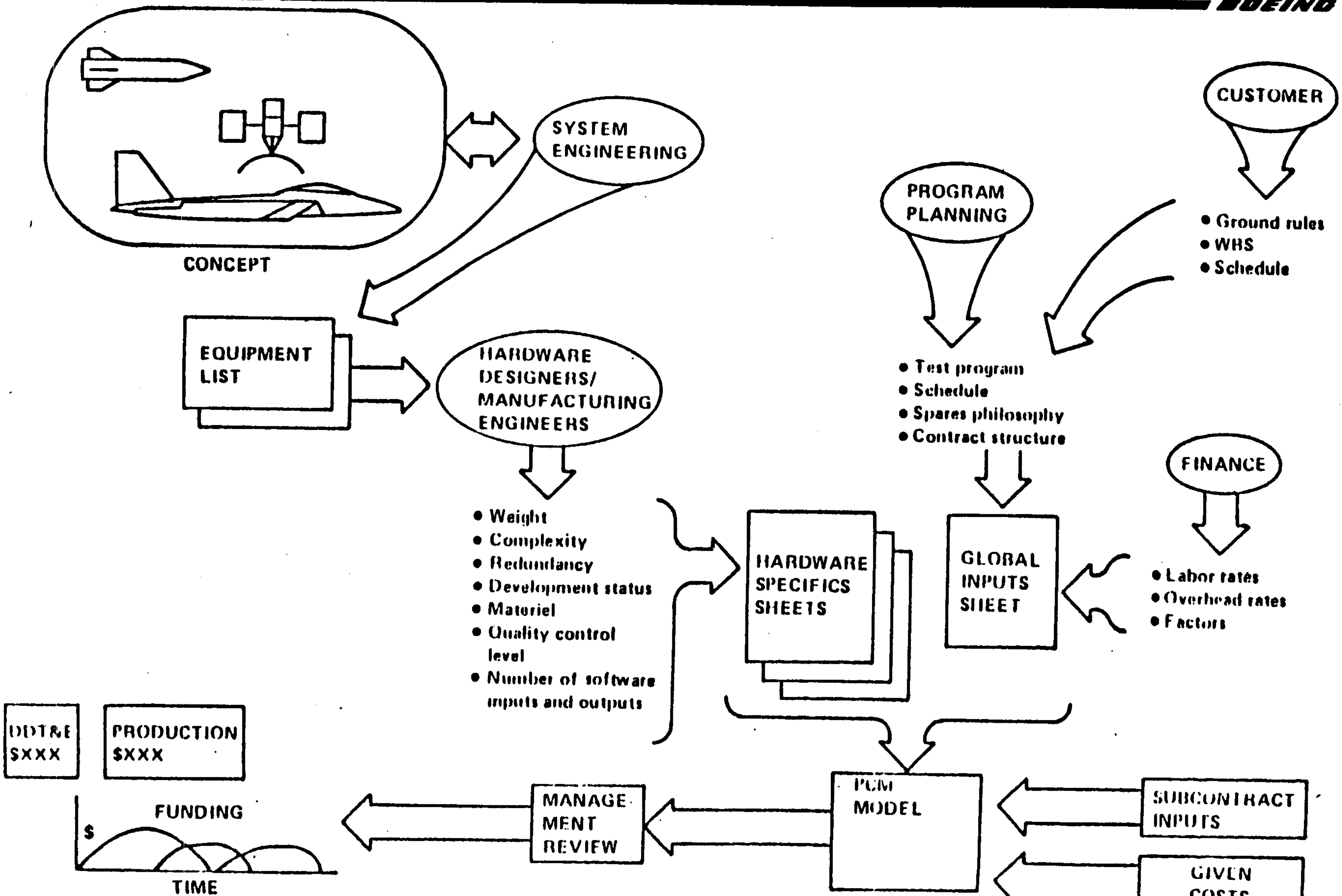
Structures and Assembly Verification Experiment (SAVE)

PCM Estimating Method



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COST SOURCE

Costs for the truss structure and utility trays were developed by the PCM based on weight, material, and complexity inputs provided by the design engineers. Costs for instrumentation, excitation, and laser optical systems were prepared by test laboratory personnel familiar with these systems, and were input to the model as given costs. These inputs included the development and testing necessary to assure feasibility and reliability in the test environment. The cost for the photogrammetry system was provided by Geodetic Services, Incorporated, and includes the hardware, development, and assistance during Orbiter integration, training, and in evaluation of results.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Cost Source

BOEING

PCM Developed (BAC)	Given Costs (BAC)	Vendor Supplied
• Truss Structure	• Instrumentation	• Photogrammetry
• Utility Trays	• Excitation	
• Labor	• Laser Optics	

COST ESTIMATE GROUND RULES AND ASSUMPTIONS

The costing approach assumes that all design, development, test, and evaluation (DDT&E) of hardware and software for the assembly fixture, truss, and utility trays, is accomplished on Space Station program budget. Those items unique to the experiment, such as the instrumentation and excitation systems and their related software, are designed and developed on SAVE program budget. Additionally, the cost of experiment hardware; i.e., trusswork and utility trays, is charged to the SAVE program. The assembly fixture cost is not charged to the SAVE program since it is returnable for use on future Space Station flights.

The PCM provides a rough order of magnitude cost in 1986 dollars. It is assumed that the hardware is built in developmental shops which have lower burdened costs. An allowance is made for spares and for engineering change and contract change proposals (ECP and CCP).

SPACE STATION

Structures and Assembly Verification Experiment
(SAVE)

Cost Estimate Ground Rules and Assumptions

BOEING

- ROM Estimate
- 1986 Dollars
- Protoflight Program - Only One Unit Built
- Hardware Built in Developmental Shops
- 10% Spares
- Allowance Included for Class I (ECP and CCP) Changes.
- D.D.T. and E. Estimated for :
  - WBS 1.3.4 Instrumentation
  - WBS 1.3.5 Excitation Subsystem
  - WBS 1.3.6 Software
- Assume Development is Completed for:
  - WBS 1.3.1 Assembly Fixture
  - WBS 1.3.2 Truss Structure
  - WBS 1.3.3 Utility Trays

COST SUMMARY

Costs are shown for hardware and support elements and for engineering and manufacturing. The major cost elements are the subsystems, accounting for over fifty percent of the total thirty-one million dollars. The substantial bias towards manufacturing costs reflects the minimal DDT&E, and the major emphasis on fabrication.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Cost Summary

BOEING

	1986 Dollars (Millions)		
	Engineering	Manufacturing	Total
Hardware			
Subsystems	3.81	15.06	18.87
Final Assembly and Checkout		2.26	2.26
Spares		1.50	1.50
Support Elements			
SE&I	0.43		0.43
Software Engr.	0.39		0.39
Systems Ground Test	0.40		0.40
Peculiar Support Equipment	0.30	0.63	0.93
Tooling and STE		3.99	3.99
Logistics	0.18		0.18
Liaison Engr.	0.09		0.09
Data	0.08		0.08
Program Mgmt.	0.54	1.13	1.67
Total	6.22	24.57	30.79

MAJOR COST ELEMENTS

This chart shows the breakdown of hardware subsystem costs. The truss structure has some engineering effort because of the experiment's unique requirement for tip mass supports. The utility trays reflect a small engineering effort; for example, preparation of procurement specifications and design liaison.

To evaluate the sensitivity of the PCM estimates to inputs, the truss structure subsystem was rerun using a complexity factor of 4 and a manufacturing learning curve of 85% which estimated a cost of $2.64 million. The initial PCM estimate of $9.73 million used a complexity factor of 8 and did not consider the benefit of the manufacturing learning curve for this type of repetitive manufacture. It is recommended that the lower cost number be utilized for estimating costs for this experiment.

The instrumentation system costs include a two and one-half million dollar laser optical system including the related DDT&E.

MAJOR COST ELEMENTS

WBS Item		1986 Dollars (Millions)	
		Engineering	Manufacturing
1.3.2	Truss Structure Subsystem	1.04	9.73/2.64
1.3.3	Utility Tray Subsystem	0.08	3.28
1.3.4	Instrumentation Subsystem	1.87	1.64
1.3.5	Excitation Subsystem	0.82	0.41
	Total	3.81	15.06/7.97

CONCLUSIONS

It is concluded that a four year experiment development and test program starting in May 1987 is feasible, but with some element of risk. The schedule is success oriented, with minimal tolerance for errors, and necessitates special emphasis by the Space Station program in developing the design of key elements such as the assembly fixture, trusses, and utility trays.

A weight budget of fifteen thousand pounds was assigned, however this was exceeded by one-third in our preliminary weight estimates. Our estimates are believed to be unconservative, therefore, further weight increases are expected as design development matures.

EVA timelines based on the tasks we have defined consume the major portion of time allotted. Some tasks and functions were not thoroughly researched, therefore we believe the timelines will grow. Consideration should be given to a possible third EVA period.

Two EVA periods were assigned for this study. Within that constraint, there was insufficient time to disassemble and return the experiment, therefore it is left on-orbit as a free flyer. Analyses showed that reboost capability was required to meet the groundrule of a three year orbital lifetime.

Structures and Assembly Verification Experiment (SAVE)

Conclusions

- Experiment weight budget increase needed
- Schedule is success oriented
- Experiment feasible - EVA timelines are marginal
- Experiment hardware not returned
- Free flyer configuration needs reboost capability

CONCERNS

The major concerns are weight, schedule, EVA construction time, and the safety aspects of jettisoning experiment elements in an emergency.

The weight problem is aggravated by the protoflight approach, where the requirement for ultimate load qualification tests will tend to drive the weight even heavier.

The schedule concern is that SAVE hardware fabrication and test is predicated on early design development and release of engineering, substantially before Space Station CDR. This increases the risk of downstream design changes.

EVA timelines developed during the study consumed nearly the entire budget allocated for this activity. The fidelity of this analysis left many unknowns which were estimated. Further one-G testing is recommended to quantify some areas of concern.

During the study, emergency jettison procedures were devised for the locked-down experiment structure, however, concerns remain for the safety and procedures to be used in the event of a mission abort command during the EVA construction phase. Separate interfaces and devices must be studied with consideration for astronaut safety and timelines.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Concerns

BOEING

- Compatibility of Experiment and Space Station Schedules
- Protoflight Concept - Weight and Cost Impact
- Timeline Margins
- Emergency Jettison Provisions - Assembly Fixture and Truss

RECOMMENDATIONS

Further design study should be directed to developing concepts for assembly and attachment of utility trays and for determining the associated timelines. Folding segments and fixed lengths with their attendant stowage and attachment peculiarities should be addressed. The tip mass design including integration of the excitation device needs further investigation. The tip mass could be distributed at four corners rather than being one single centrally located mass, to simplify EVA installation. Study is required to define the interfaces, devices, procedures and safety considerations for emergency jettison during all stages of construction.

Ground tests using neutral buoyancy facilities and foam core mockups are needed to support the design study with data on feasibility and to aid in refinement of timeline estimates.

Further analyses are required to evaluate the dynamic characteristics of the structure/assembly fixture combination during various phases of construction with regard for the three-tenths Hertz minimum frequency design requirement. The effect of orbiter vernier firings and construction activity loads needs to be considered in this scenario. Additional analyses are required for a more thorough understanding of combined orbiter/experiment dynamics. In this study, the experiment was treated as being fixed to a rigid orbiter for purposes of simplification. Instead, the orbiter has its own particular stiffness characteristics that will interact with the experiment as a combined system.

The RMS was used extensively in this study to perform routine functions and maximize the productivity of EVA. Simulations and analyses should be performed to verify that assigned RMS functions can indeed be performed.

Location, quantity and element delivery capabilities of canisters requires further study in an effort to better understand and possibly reduce the timelines. Some degree of automated part delivery or indexing warrants consideration.

The cost and requirements for a free flyer bus to provide guidance, control and reboost were defined in the study. Items not addressed and requiring further definition are: weight, orbiter stowage volume, packaging, assembly timelines and impact on experiment program schedule.

SPACE STATION

Structures and Assembly Verification Experiment (SAVE)

Recommendations

BOEING

Areas of Further Study

- Design and Installation of Utility Trays
- Design of Contingency Separation System
- Assembly Fixture/Truss System Stiffness
- Ground Testing to Validate Assembly Concepts and Timelines
- Validate RMS Usage
- Orbiter /Experiment Dynamic Interactions
- Canister Placement and Degree of Delivery Automation
- Design/Integration of Tip Mass and Excitation Device
- Free Flyer Implementation

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SECTION II

Langley Research Center Dynamic Analysis Study

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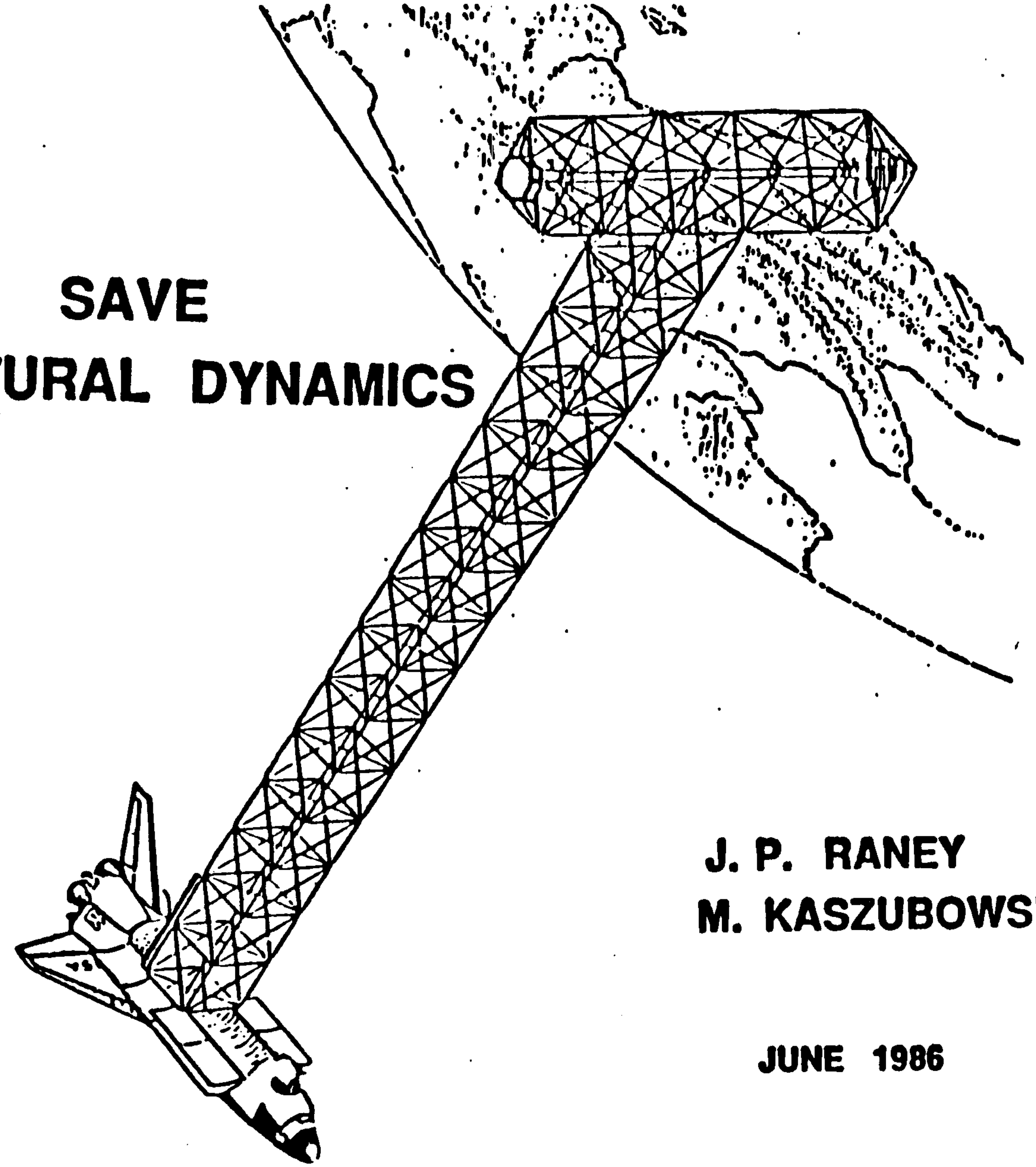
SAVE
STRUCTURAL DYNAMICS



J. P. RANEY
M. KASZUBOWSKI

JUNE 1986

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THE JOINTS (NODES) WERE MODELLED AS POINT MASSES.

THE SHUTTLE (ORBITER) WAS MODELLED AS A RIGID (SOLID) BODY.

THE ATTACHMENT INTERFACE WAS MODELLED AS A FLEXIBLE CONNECTION WITH LINEAR SPRINGS AT EACH PHYSICAL POINT OF ATTACHMENT. THE STIFFNESS VALUES USED ARE SHOWN IN THE TABLE "ASSEMBLY AND EXPERIMENT FIXTURE STIFFNESS".

MSC NASTRAN MODEL

- o 8 & 16 Bay Truss Models, 4 Bay "T", Two 453.4 Kg Tip Masses
- o Utility Trays: 2286.1 Kg, Non-Load Carrying, On 8 Bays Nearest Orbiter
- o Truss Member Properties

  $E = 2.7579 \times 10^{11}\ nt/m^2$

  $A = 2.359 \times 10^{-4}\ m^2$

  $\rho = 1743.8\ Kg/m^3$

- o Joint Mass: 5.2 Kg Each
- o Orbiter Properties:

  $Mass = 106757\ Kg$

  $I_{Pitch} = 1.0167 \times 10^{7}\ Kg\text{-}m^2$

  $I_{Roll} = 1.3598 \times 10^{6}\ Kg\text{-}m^2$

  $I_{Yaw} = 1.0641 \times 10^{7}\ Kg\text{-}m^2$

- o 510 Degrees Of Freedom

THIS FIGURE SHOWS THE 16 BAY SAVE STRUCTURE. THE FOLLOWING FEATURES SHOULD BE KEPT IN MIND WHILE READING THIS REPORT :

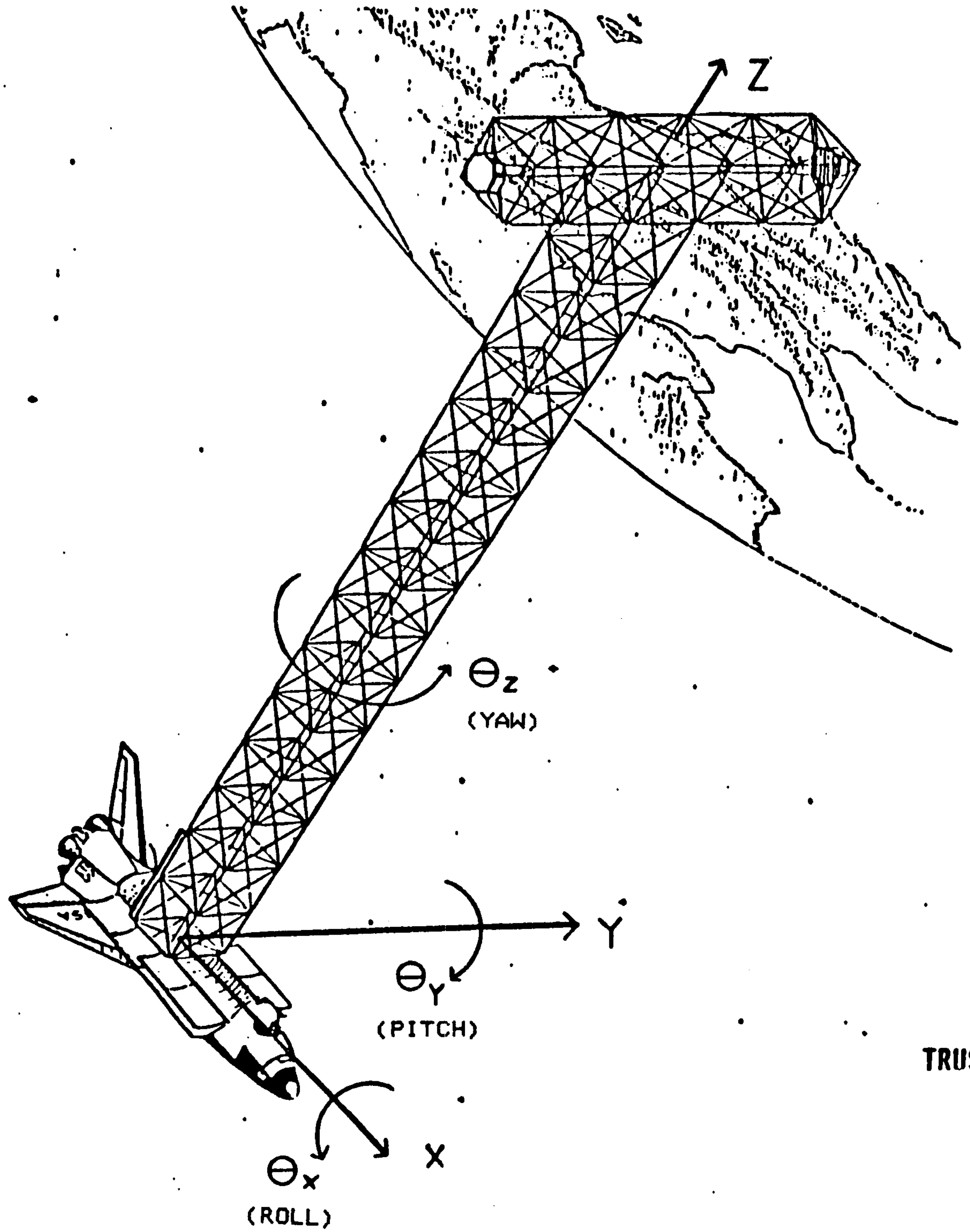
1. THE STRUCTURE IS TO BE ASSEMBLED IN THE ORBITER Z-AXIS

2. THE 4 BAY "T" SECTION IS ORIENTED PERPENDICULAR TO THE ORBITER PAYLOAD BAY.

3. ONE 453.4 KG TIP MASS IS LOCATED ON EACH TIP OF THE "T"

4. THE COORDINATE SYSTEM IS ALSO SHOWN ON THIS FIGURE.

   X -- ROLL AXIS
   Y -- PITCH AXIS
   Z -- YAW AXIS



TRUSS ORIENTATION

THE TOTAL MASS SUMMARY INCLUDES THE MASS OF THE ORBITER, 8 BAYS OF UTILITY TRAYS, THE TIP MASSES, AND 16 BAYS OF BASE TRUSS WITH A 4 BAY "T" SECTION. THE ATTACHMENT FIXTURE IS NOT INCLUDED, NOR IS ANY ADDITIONAL HARDWARE REQUIRED FOR THE TRUSS TO BECOME A FREE FLYER. FINALLY, IT IS ASSUMED THAT THE INSTRUMENTATION IS PART OF THE TIP MASS.

SAVE MASS SUMMARY

TOTAL SYSTEM MASS	111,018.6	KG
SHUTTLE MASS	106,757	KG
TRAY MASS	2,286.1	KG
TIP MASSES	906.8	KG
STRUCTURE MASS	1,068.7	KG

VIBRATION MODE ANALYSIS EVALUATED THE EFFECTS OF CONFIGURATION GEOMETRY, TIP MASS, ATTACHMENT FIXTURE STIFFNESS, UTILITY TRAY PLACEMENT, AND MISSING MEMBERS (LONGERON, BATTEN, OR DIAGONAL).

SINUSOIDAL RESPONSE ANALYSIS EVALUATED THE STEADY STATE TIP ACCELERATIONS, DISPLACEMENTS, AND MEMBER FORCES IN THE TRUSS SECTION NEAREST THE ORBITER.

THE ACCELERATIONS AND LOADS PRODUCED BY SELECTED FIRING SCENARIOS OF THE PRIMARY THRUSTERS WERE COMPUTED.

STRUCTURAL DYNAMICS ANALYSIS

Critical Aspects Of Dynamic Response Were Studied Including:

- o **Vibration Modes**
  - Geometry And Tip Mass Requirements
  - Attachment Stiffness Requirements
  - Utility Tray Effects On Bending & Torsional Frequencies
  - Missing Member Effects On Frequencies
- o **Sinusoidal Response**
  - Response To Sinusoidal Excitation Applied At Tip
- o **Primary RCS Dynamics**
  - Effects Of Primary Rcs Firing On Structural Loads And Motions

THE COMPLETE COLLECTION OF CONFIGURATIONS AND PARAMETER VARIATIONS IS SUMMARIZED IN THIS TABLE.

DYNAMIC ANALYSIS MATRIX

OUTPUT / MODEL	MODES & FREQUENCIES											LOADS										
												STATIC TIP				SINE TEST				PRCS		
PRIORITY	H	H	H	H	H	M	M	M	H	L	L	H	H	M	M	H	H	M	M	M	H	M
NO. OF BAYS	16	16	16	16	16	16	16	16	8	8	8	16	16	8	8	16	16	16	16	16	16	8
ATTACH LOCATION	B	B	B	S	S*	B	B	B	B	B	B	B	S	B	S	B	B	B	B	B	B	B
I/F STIFFNESS	R	R	Y	@	@	@	@	@	R	R	R	R	R	R	R	#	#	#	#	#	#	#
UTILITY TRAYS	N	Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	Y	N	N	Y	Y	Y	Y	Y	Y	N
MEMBER OUT						L	D	B		L	D							L	D	B		

LEGEND:

PRIORITY: H = HIGH, M = MEDIUM, L = LOW

ATTACH LOC.: B = BASE, S= SIDE, S* = SIDE WITH LOCK OUT ON FWD NODES

I/F STIFF.: R = RIGID, V = VARIATION, # = SPECIFIC VALUE, @ = SPECIFIC VALUE

UTILITY TRAYS : Y = YES, N = NO

MEMBER OUT ; L = LONGERRON, D = DIAGONAL, B = BATTEN

A SUMMARY OF THE MODAL ANALYSIS CASES IS GIVEN ON THIS CHART.

VIBRATION MODES

- NUMBER OF BAYS : 8 AND 16

- SAVE / ORBITER ATTACHMENT :

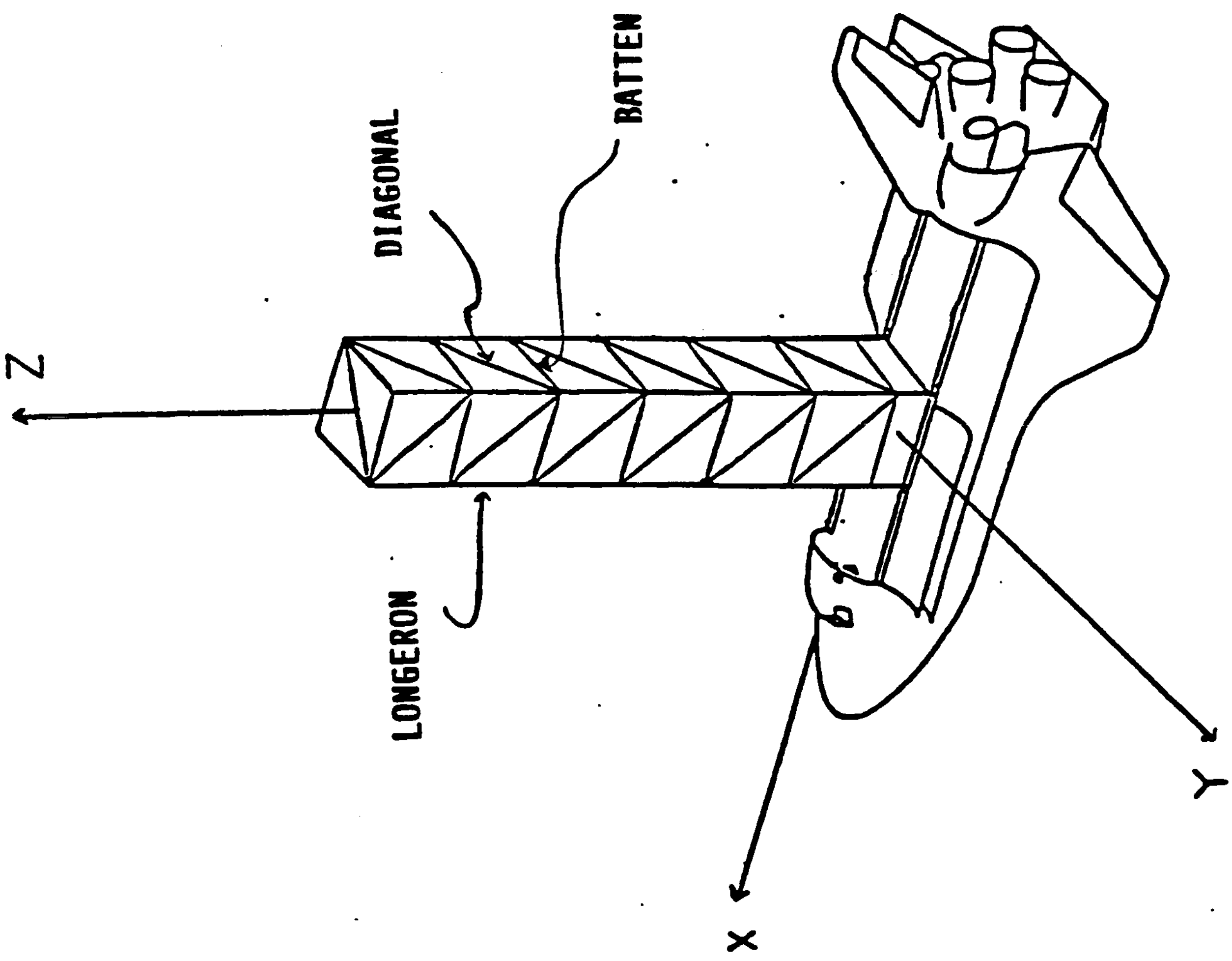
  ASSEMBLY FIXTURE SIDE MOUNTED
  EXPERIMENT FIXTURE BASE MOUNTED

- UTILITY TRAYS : WITH AND WITHOUT

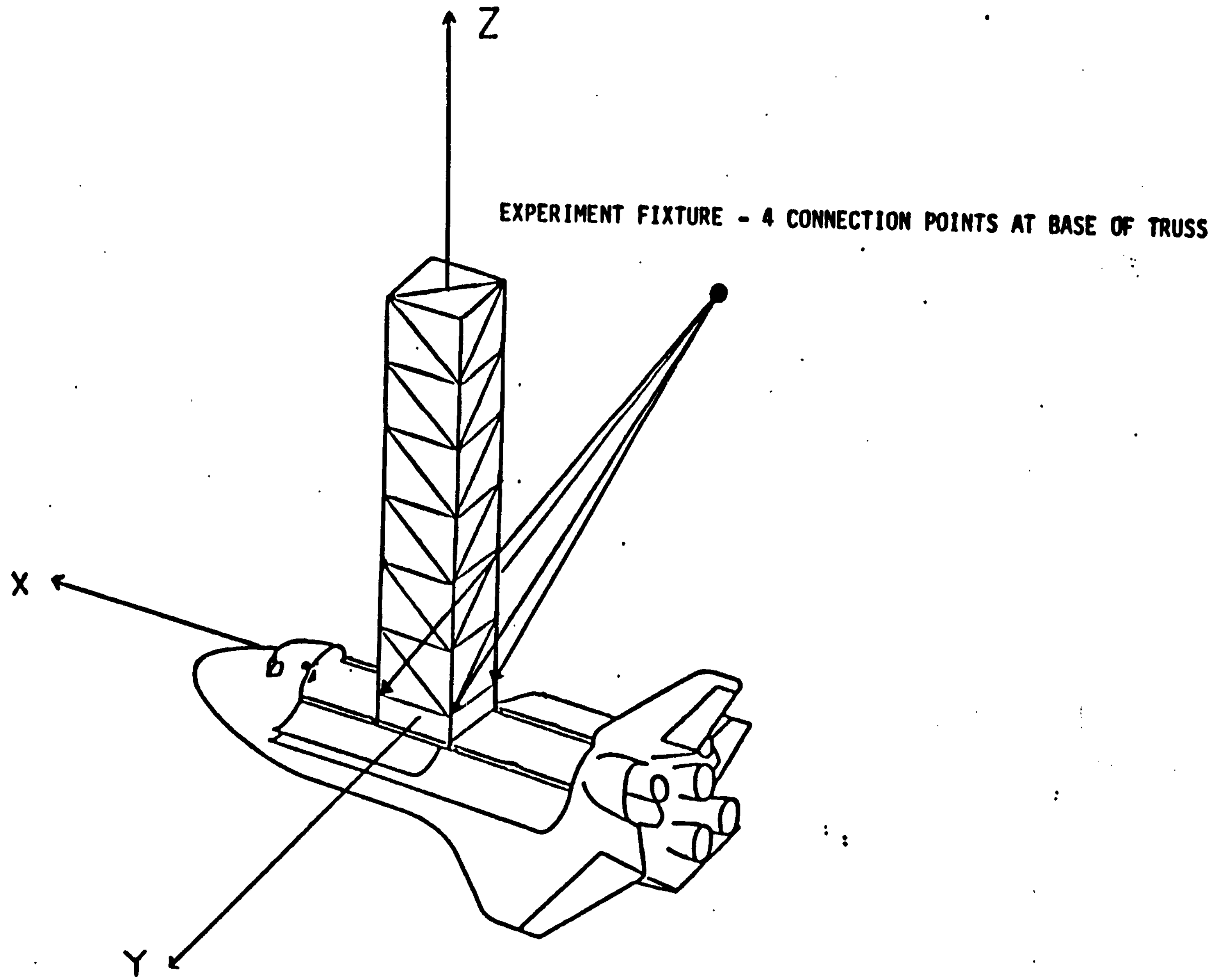
- MEMBER OUT : LONGERON / DIAGONAL / BATTEN

THIS FIGURE SHOWS A TYPICAL LONGERON, BATTEN, AND DIAGONAL.

TRUSS MEMBERS

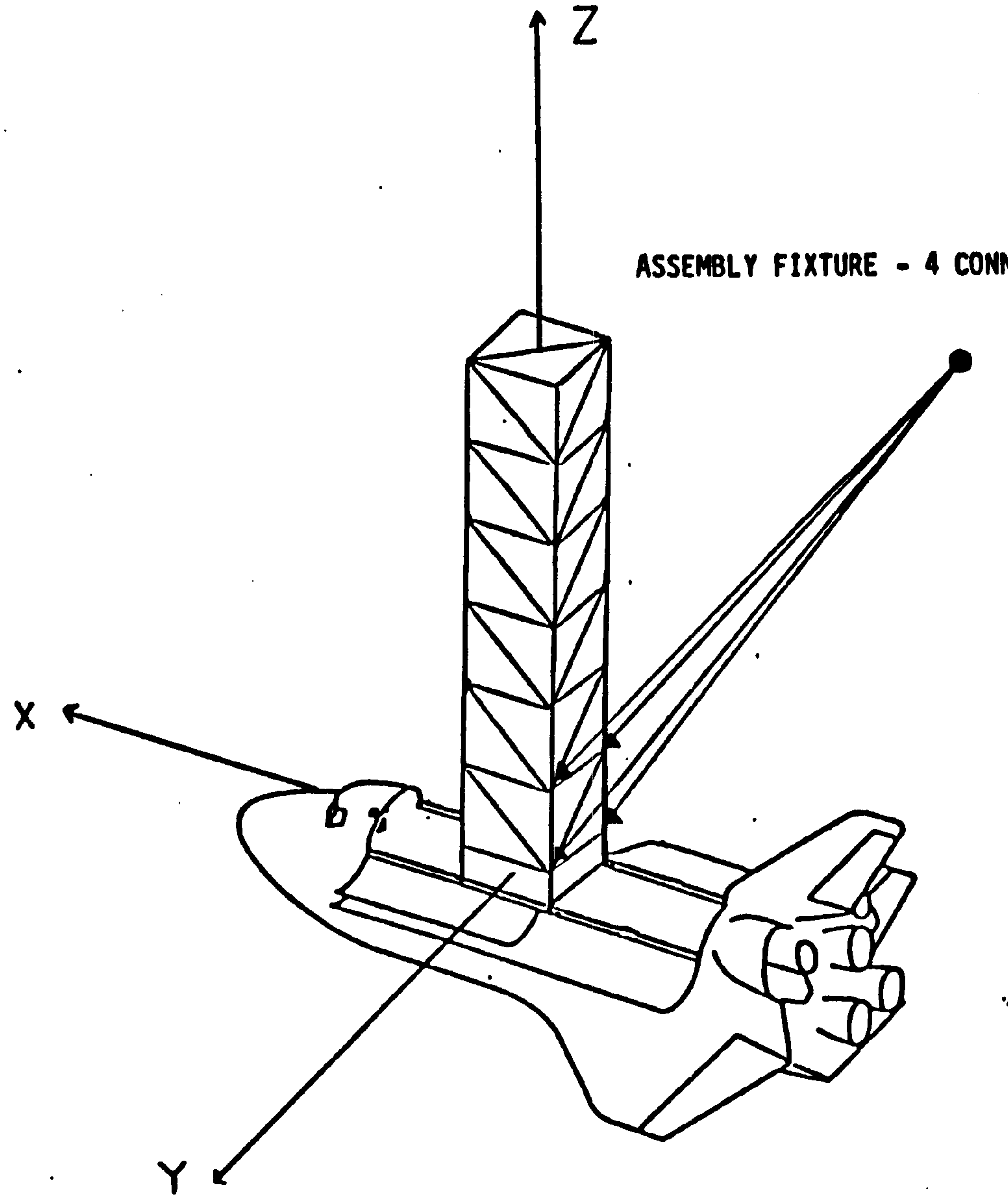


THIS FIGURE SHOWS THE 4 CONNECTION POINTS FOR THE EXPERIMENT FIXTURE.

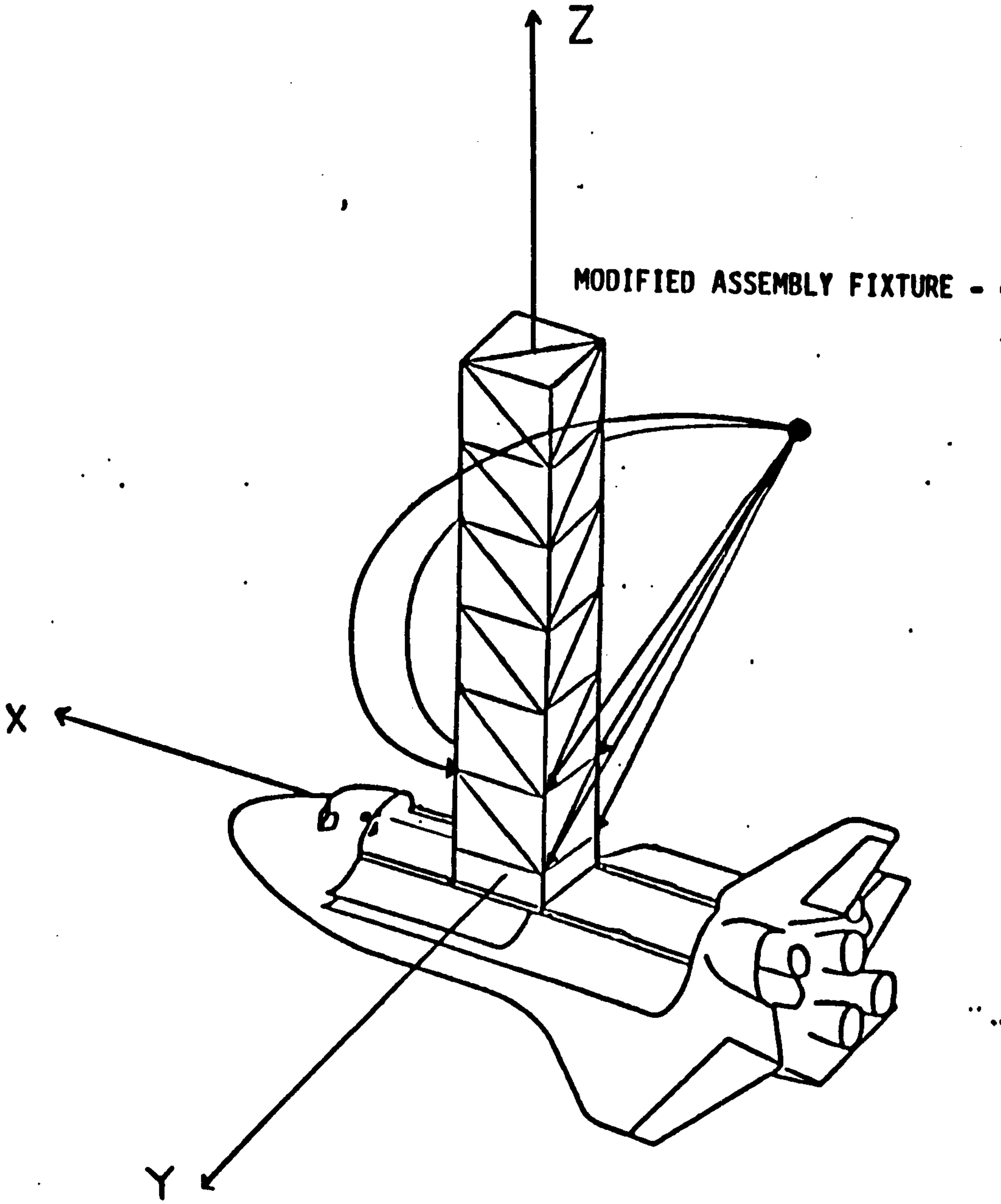

Z
EXPERIMENT FIXTURE - 4 CONNECTION POINTS AT BASE OF TRUSS
X
Y

THIS FIGURE SHOWS THE 4 CONNECTION POINTS FOR THE ASSEMBLY FIXTURE.

ASSEMBLY FIXTURE - 4 CONNECTION POINTS ON AFT SIDE OF TRUSS



THIS FIGURE SHOWS THE 6 CONNECTION POINTS FOR THE MODIFIED ASSEMBLY FIXTURE.



MODIFIED ASSEMBLY FIXTURE - 4 CONNECTION POINTS ON AFT SIDE AND 2 CONNECTION POINTS ON FORE SIDE OF TRUSS

THE EFFECT THAT ADDING UTILITY TRAYS HAS ON THE NATURAL FREQUENCIES OF THE SYSTEM IS SHOWN IN THE FOLLOWING TWO TABLES. NOTE THAT THE ATTACHMENT POINT STIFFNESS IS INFINITY FOR THESE CALCULATIONS.

BY PLACING THE TRAYS ON THE 8 BAYS NEARER THE ORBITER, THEIR ABSOLUTE MOTION, AND HENCE THEIR EFFECT ON THE LOWEST BENDING AND TORSIONAL NATURAL FREQUENCIES, WAS MINIMIZED. THEY ARE, HOWEVER, IN THE POSITION OF MAXIMUM RELATIVE DISPLACEMENT (STRAIN) AND IN THIS POSITION MAY HAVE THE GREATEST INFLUENCE ON DAMPING.

UTILITY TRAY ANALYSIS *

(TRAYS INSTALLED ON 8 BAYS NEAREST ORBITER)

	EXPERIMENT FIXTURE			ASSEMBLY FIXTURE		
MODE	WO/TRAYS	W/TRAYS	% DECRE	WO/TRAYS	W/TRAYS	% DECRE.
1ST BENDING	0.5984 HZ	0.5961 HZ	0.38 %	0.6005 HZ	0.5973 HZ	0.54 %
1ST TORSION	0.8894 HZ	0.8668 HZ	2.6%	0.9316 HZ	0.9074 HZ	2.7%

*USES RIGID ATTACHMENT TO ORBITER

THIS TABLE SHOWS THAT WHEN THE UTILITY TRAYS WERE POSITIONED ON THE 8 BAYS NEARER THE TIP, THE EFFECT ON THE LOWEST NATURAL FREQUENCIES IS GREATER THAN WHEN THEY WERE PLACED NEAR THE ORBITER.

IN THIS POSITION THE TRAYS EXPERIENCE GREATER ABSOLUTE MOTION IN THE AFFECTED MODES AND, HENCE, HAVE GREATER EFFECT ON REDUCING THE NATURAL FREQUENCIES.

UTILITY TRAY ANALYSIS*

(TRAYS INSTALLED ON 8 BAYS NEAREST TIP)

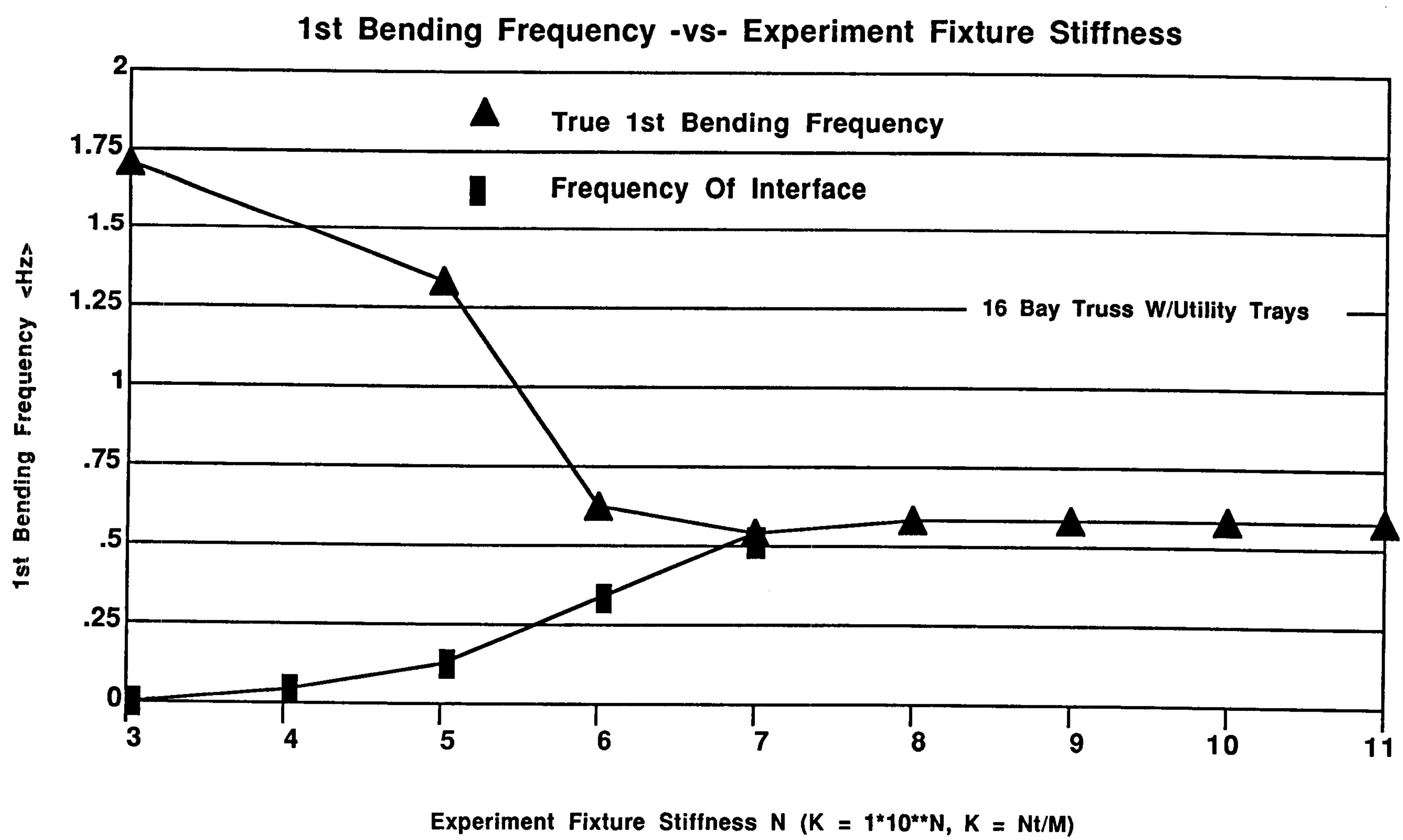
	EXPERIMENT FIXTURE			ASSEMBLY FIXTURE		
MODE	WO/TRAYS	W/TRAYS	% DECRE.	WO/TRAYS	W/TRAYS	% DECRE.
1ST BENDING	0.5984 HZ	0.5329 HZ	12.3%	0.6005 HZ	0.53443 HZ	12.3%
1ST TORSION	0.8894 HZ	0.8490 HZ	4.8%	0.9316 HZ	0.8904 HZ	4.6%

*USES RIGID ATTACHMENT TO ORBITER

THE EFFECT THAT VARYING THE STIFFNESS OF THE ATTACHMENT FIXTURE HAD ON THE 1ST BENDING FREQUENCY IS SHOWN ON THIS FIGURE. BELOW A CRITICAL STIFFNESS OF 10**7 NT/M TWO MODES APPEARED: THE RIGID BODY MODE WHICH APPROACHED ZERO FREQUENCY, AND THE FIRST FREE-FREE BENDING MODE WHICH INCREASED AS THE ATTACHMENT STIFFNESS APPROACHED ZERO.

THEREFORE, IN ORDER TO MAINTAIN THE FIRST BENDING MODE NEAR .5 HZ IT IS NECESSARY TO MAINTAIN THE STIFFNESS OF THE ATTACHMENT FIXTURE ABOVE 10**7 NT/M.

ATTACHMENT FIXTURE STIFFNESS REQUIREMENTS



ESTIMATED STIFFNESSES OF THE EXPERIMENT AND ASSEMBLY FIXTURES ARE PRESENTED IN THIS TABLE. THE VALUES SHOWN ARE BASED ON THE LOAD CARRYING CHARACTERISTICS OF THE ORBITER PAYLOAD BAY.

(NOTE: FUTURE ANALYSES WILL INCORPORATE DETAILED FINITE ELEMENT MODELLING OF THE ATTACHMENT FIXTURES AND ORBITER SILLS.)

ASSEMBLY AND EXPERIMENT FIXTURE STIFFNESS

	EXPERIMENT FIXTURE STIFFNESS (10^7 nt/m)			ASSEMBLY FIXTURE STIFFNESS (10^7 nt/m)			MODIFIED ASSEMBLY FIXTURE STIFFNESS (10^7 nt/m)		
	X	Y	Z	X	Y	Z	X	Y	Z
FORWARD	3.8	0.2	1.25	0	0	0	3.9	2.5	4.1
AFT	4.1	0.4	3.8	3.2	2.5	5.8	3.2	0	5.8

NATURAL FREQUENCIES OF THE ORBITER/SAVE STRUCTURE CONNECTED BY THE EXPERIMENT AND ASSEMBLY FIXTURES (SEE PREVIOUS TABLE) ARE GIVEN IN THIS TABLE.

TWO CONFIGURATIONS WERE EXAMINED: THE 8 BAY STRUCTURE THAT WOULD EXIST AT THE END OF THE FIRST DAY'S ASSEMBLY ACTIVITIES, AND THE 16 BAY FINAL TEST CONFIGURATION.

SUMMARY OF ATTACHMENT FIXTURE ANALYSIS

	MODE	EXP. FIXT.	ASS. FIXT.	MOD. ASS. FIXT.
8 BAYS (W / O TRAYS)	1ST BENDING	1.381 HZ	1.356 HZ	1.598 HZ
	1ST TORSION	1.1657 HZ	1.149 HZ	1.278 HZ
16 BAYS (W / TRAYS)	1ST BENDING	0.5594 HZ	0.5249 HZ	0.6124 HZ
	1ST TORSION	0.8481 HZ	0.8593 HZ	0.8758 HZ

THIS TABLE SHOWS THE CHANGE IN THE NATURAL FREQUENCIES WHEN EITHER A LONGERON, A BATTEN, OR A DIAGONAL WERE REMOVED FROM THE TWO CONFIGURATIONS OF THE PREVIOUS TABLE (WITH THE EXPERIMENT FIXTURE ONLY).

IN EACH CASE THE MEMBER WAS REMOVED FROM THE BAY NEAREST THE ORBITER IN ORDER TO PRODUCE A MODIFIED BOUNDARY CONDITION. (ACTUAL STRUCTURAL PARAMETERS CAN BETTER BE INFERRED FROM SEVERAL SETS OF TEST DATA FOR DIFFERENT BOUNDARY CONDITIONS).

SUMMARY OF MEMBER OUT ANALYSIS
(EXPERIMENT FIXTURE ONLY)

	8 BAYS		16 BAYS	
	1ST BENDING	1ST TORSION	1ST BENDING	1ST TORSION
TRUSS IN TACT	1.381 HZ	1.167 HZ	0.5594 HZ	0.8482 HZ
LONGERON REMOVED	1.221 HZ (13.1%)*	1.013 HZ (15.27.)*	0.5026 HZ (11.3%)*	0.8093 HZ (4.8%)*
DIAGONAL REMOVED	1.375 HZ (0.44%)*	1.035 HZ (12.8%)*	0.5510 HZ (1.5%)*	0.8202 HZ (3.4%)*
BATTEN REMOVED	1.373 HZ (0.58%)*	1.040 HZ (12.2%)*	0.5529 HZ (1.2%)*	0.8187 HZ (3.6%)*

*PERCENT DECREASE FROM INTACT CONFIGURATION

THE RESULTS SHOWN IN THIS AND THE NEXT TABLE WERE CALCULATED FOR A CANTILEVERED BOUNDARY CONDITION AT THE BAY NEAREST THE ORBITER. THERE WAS NO ATTACHMENT STRUCTURE INCLUDED IN THE STATIC CALCULATIONS.

THE ASSEMBLY FIXTURE IS STIFFER THAN THE EXPERIMENT FIXTURE IN BOTH THE X AND Y (BENDING) DIRECTIONS.

STATIC ANALYSIS RESULTS
(8 BAYS)

	ASSEMBLY FIXTURE		EXPERIMENT FIXTURE	
	+X TIP FORCE	+ Y TIP FORCE	+X TIP FORCE	+Y TIP FORCE
TIP FORCE / MAX TIP DEFLECTION	426.0 LBF / IN	643.0 LBF / IN	360 LBF / IN	388 LBF / IN
TIP FORCE / MAX ELEMENT FORCE (COMPRESSION)	0.32 LBF / LBF	0.24 LBF / LBF	0.27 LBF / LBF	0. 22 LBF / LBF
MAX ELEMENT FORCE / MAX. TIP DEFLECTION	1331 LBF / IN	2679 LBF / IN	1333 LBF / IN	1764 LBF / IN

THE RESULTS SHOWN IN THIS TABLE REFLECT THE GREATER FLEXIBILITY OF THE 16 BAY CONFIGURATION. THIS IS DUE SOLELY TO ITS GREATER LENGTH.

THIS AND THE PREVIOUS TABLE MAY BE USEFUL TO ANALYSTS WHO WISH TO COMPARE THEIR MODEL OF THIS STRUCTURE WITH THE MODEL USED IN THIS STUDY.

STATIC ANALYSIS RESULTS
(16 BAYS)

	ASSEMBLY FIXTURE		EXPERIMENT FIXTURE	
	+X TIP FORCE	+ Y TIP FORCE	+X TIP FORCE	+Y TIP FORCE
TIP FORCE / MAX TIP DEFLECTION	51.0 LBF / IN	67.3 LBF / IN	50.3 LBF / IN	52.6 LBF / IN
TIP FORCE / MAX ELEMENT FORCE (COMPRESSION)	0.13 LBF / LBF	0.10 LBF / LBF	0.12 LBF / LBF	0.10 LBF / LBF
MAX ELEMENT FORCE / MAX. TIP DEFLECTION	392 LBF / IN	673 LBF / IN	419 LBF / IN	526 LBF / IN

FOR THE SINUSOIDAL RESPONSE ANALYSIS A FORCING FUNCTION (ACTING IN THE X DIRECTION) WAS MODELLED AT EACH TIP. THE FOLLOWING TWO CASES WERE CONSIDERED:

1. IN THE FIRST CASE THE FORCING FUNCTIONS ACTED IN THE SAME DIRECTION AT ALL TIMES. THIS IS CALLED THE "IN PHASE" CASE. RESULTS FOR THIS CASE ARE GIVEN AS RATIOS TO THE TOTAL FORCE PRODUCED BY THE FORCING FUNCTIONS.

2. IN THE SECOND CASE THE FORCING FUNCTIONS ACTED IN OPPOSITE DIRECTIONS AT ALL TIMES. THUS, THEY WERE 180 DEGREES "OUT OF PHASE". RESULTS FOR THIS CASE ARE GIVEN AS RATIOS TO THE TOTAL TORQUE PRODUCED BY THE FORCING FUNCTIONS.

MODAL DAMPING OF 0.5% WAS USED FOR ALL CALCULATIONS.

ALL CALCULATIONS USE THE EXPERIMENT FIXTURE STIFFNESSES AND A 16 BAY TRUSS.

CALCULATIONS WERE ALSO MADE FOR THE VARIOUS BOUNDARY CONDITIONS CREATED BY REMOVING A LONGERON, BATTEN, OR DIAGONAL FROM THE TRUSS BAY NEAREST THE ORBITER.

RESPONSES FOR OTHER VALUES OF DAMPING MAY BE USEFUL IN EVALUATION OF FUTURE EXPERIMENTAL DATA.

SINUSOIDAL RESPONSE ANALYSIS

- 16 Bay Truss Structure
- Utility Trays On 8 Bays Nearest Orbiter
- Damping Ratio = 1/2%
- 2 Periodic Forces - One On Each Tip
  - Forces "In Phase" - Both Forces Act In Same Direction At All Times
  - Forces "Out Of Phase" - Forces Act In Opposite Directions At All Times

THE STEADY STATE RESPONSES FOR THE CASE WHERE THE FORCING FUNCTIONS ARE IN PHASE ARE GIVEN IN THIS TABLE AND ON THE FOLLOWING TWO FIGURES.

SINUSOIDAL RESPONSE ANALYSIS
(FORCES IN PHASE)

			+Y TIP RESPONSE		-Y TIP RESPONSE		MAX. MEMBER LOAD AT BASE nt/nt
		F (Hz)	MAX. DISP. cm/nt	MAX. ACC. $(m/s^2)/nt$	MAX. DISP. cm/nt	MAX. ACC. $(m/s^2)/nt$	
MODE #1 1ST BENDING	TRUSS INTACT	0.5594	0.0189	0.023	0.374	0.046	-160.0
	LONGERON REMOVED	0.5026	0.209	0.021	0.317	0.031	-279.7
	BATTEN REMOVED	0.5529	0.138	0.016	0.334	0.040	-192.1
	DIAGONAL REMOVED	0.5510	0.171	0.02	0.427	0.051	-111.2
MODE #2 1ST TORSION	TRUSS INTACT	0.8482	0.0317	0.01	0.0273	0.0076	-13.7
	LONGERON REMOVED	0.8093	0.004	0.001	0.005	0.0013	-4.69
	BATTEN REMOVED	0.8187	0.0607	0.016	0.041	0.011	-18.9
	DIAGONAL REMOVED	0.8202	0.059	0.015	0.0402	0.01	-18.6

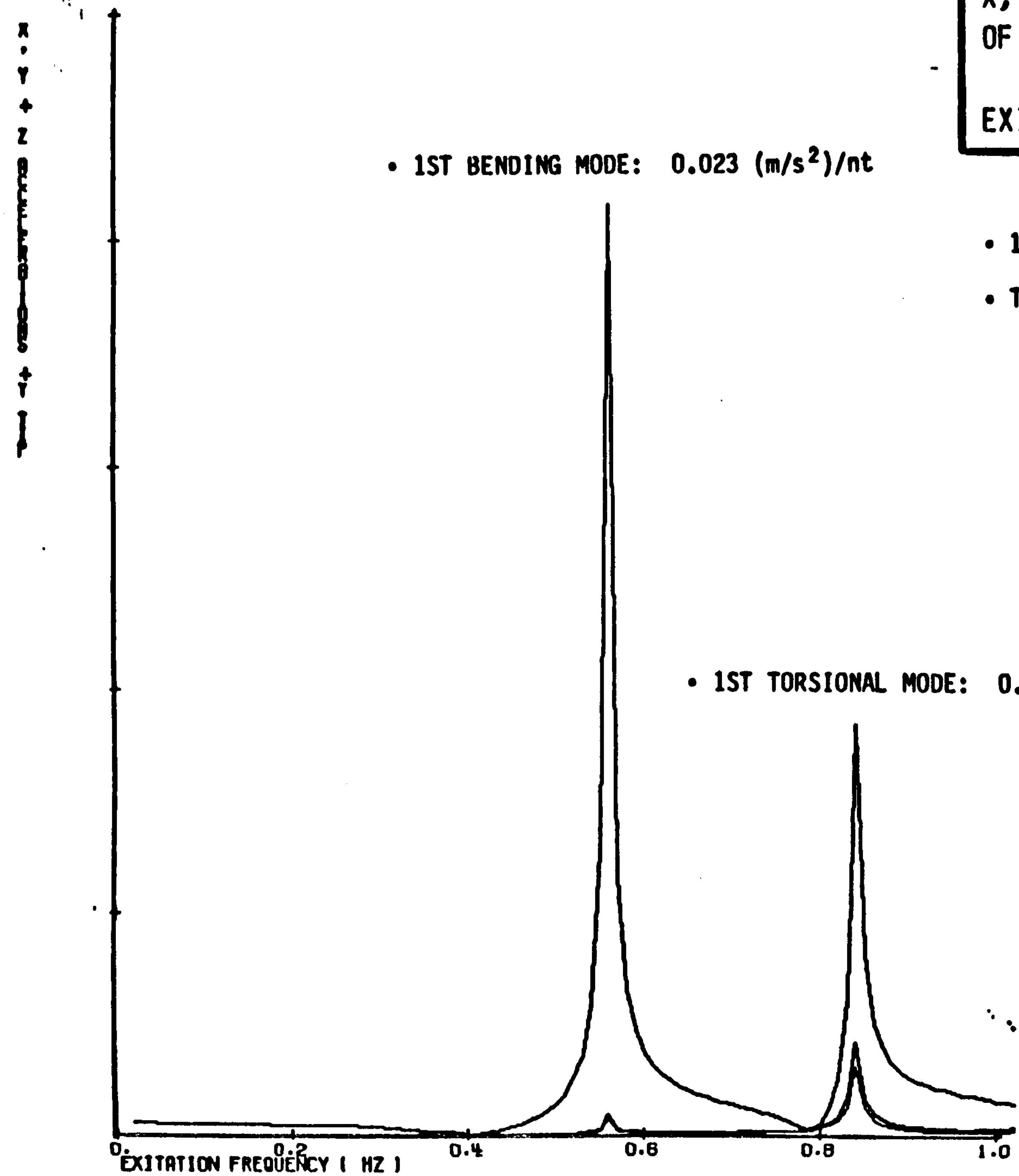
ON THIS FIGURE THE ACCELERATION RESPONSES OF THE TIP ARE GIVEN FOR THE 16 BAY INTACT STRUCTURE WITH THE TIP FORCES IN PHASE.

AS EXPECTED, THE ACCELERATION IN THE DIRECTION OF FORCING (X DIRECTION) WAS MUCH GREATER THAN IN THE Y AND Z DIRECTION. HOWEVER, THE Y AND Z ACCELERATIONS WERE PRESENT AT THE FIRST MODE FREQUENCY BECAUSE OF THE ASYMMETRIC STRUCTURAL GEOMETRY. THIS GEOMETERY ALSO YIELDED A SIGNIFICANT TORSIONAL RESPONSE WHEN EXCITATION WAS APPLIED AT THE 1ST TORSIONAL MODE FREQUENCY.

X, Y & Z ACCELERATIONS
OF +Y TIP (m/s^2)/(NT)
-VS-
EXITATION FREQUENCY (Hz)

• 16 BAY TRUSS - INTACT

• TIP FORCES IN PHASE



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THE AXIAL LOADS IN THE LONGERONS IN THE BAY NEAREST THE ORBITER ARE SHOWN ON THIS FIGURE.

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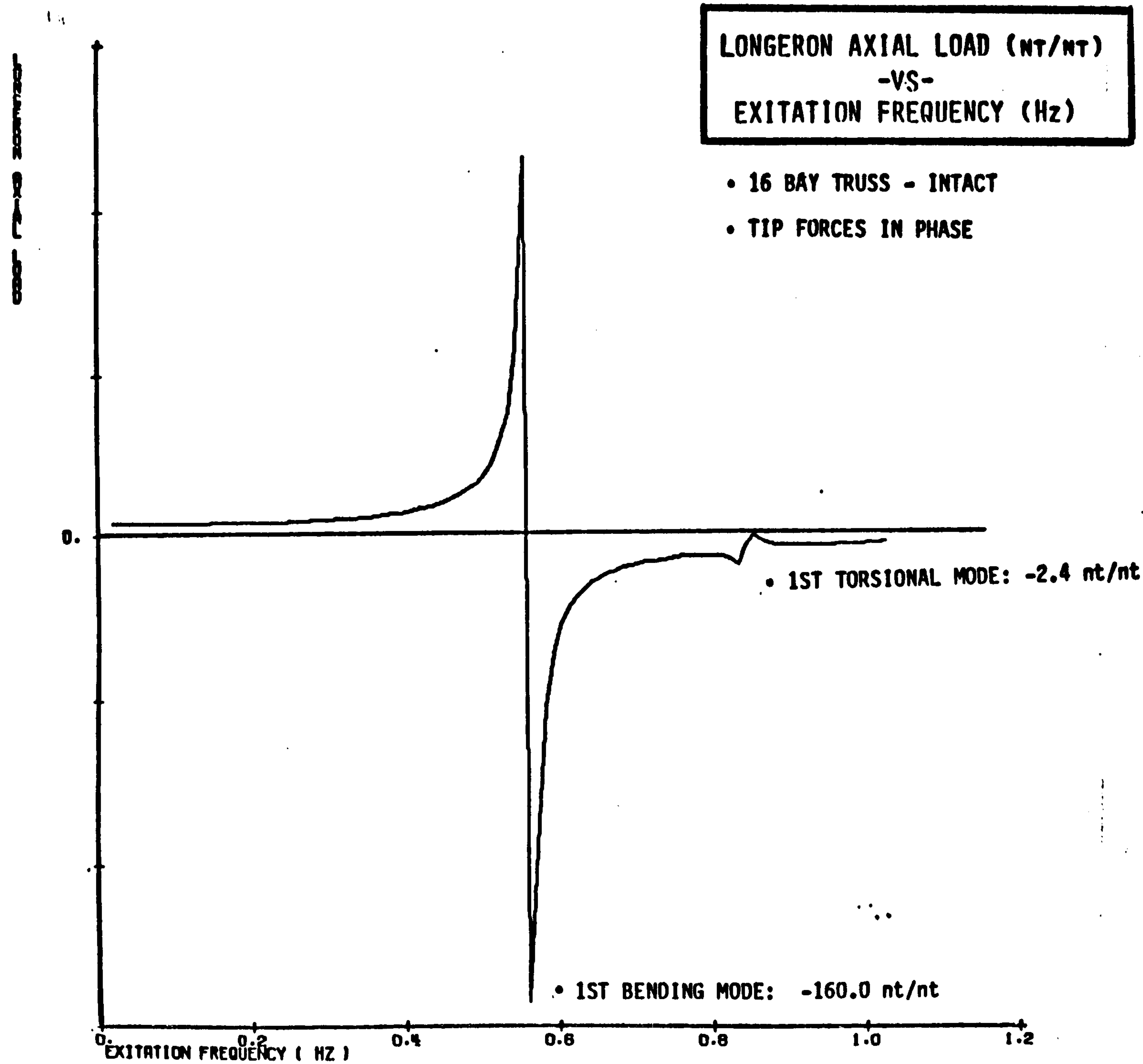
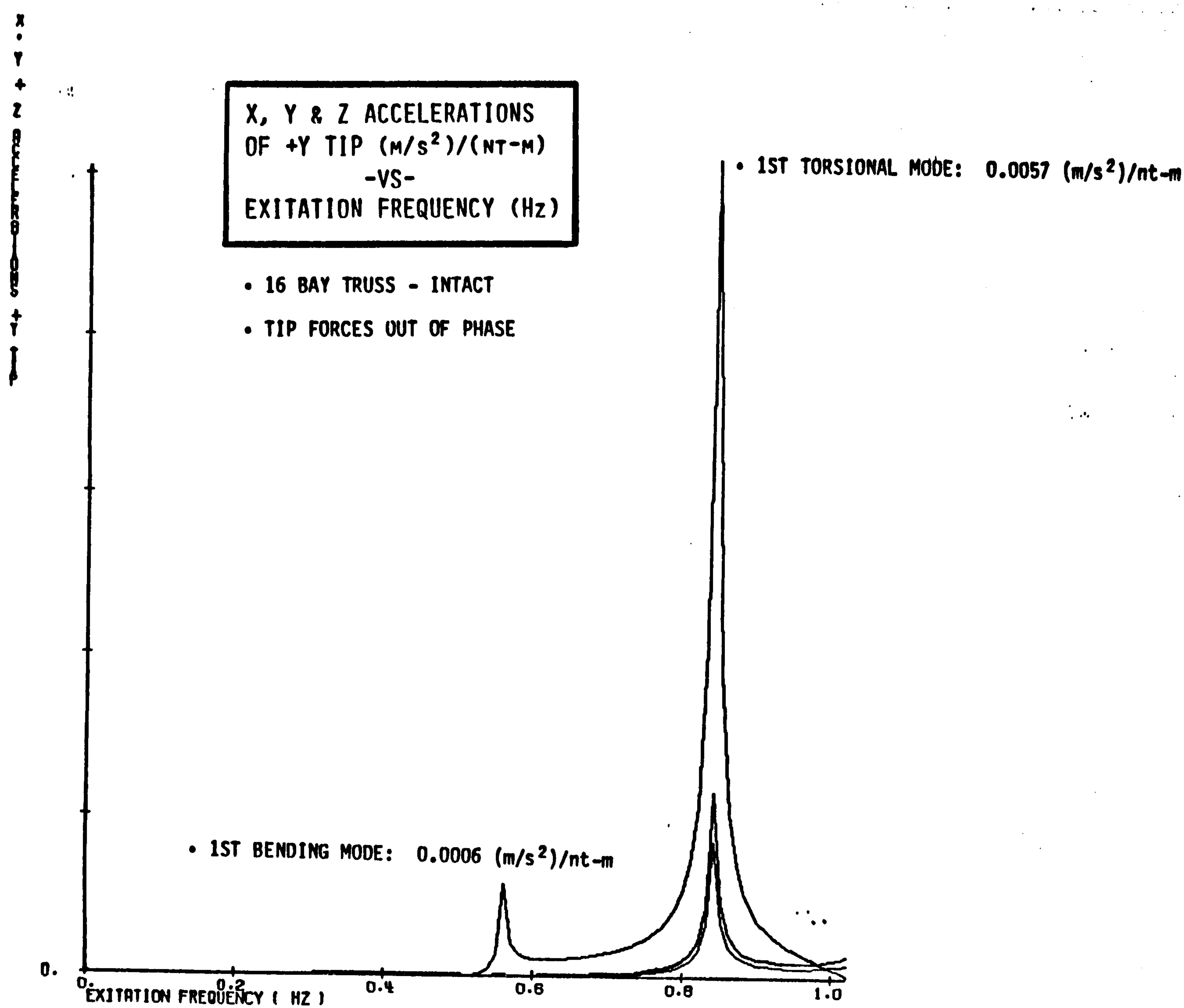


THE STEADY STATE RESPONSES FOR THE CASE WHERE THE FORCING FUNCTIONS ARE 180 DEGREES OUT OF PHASE ARE GIVEN IN THIS TABLE AND ON THE FOLLOWING TWO FIGURES.

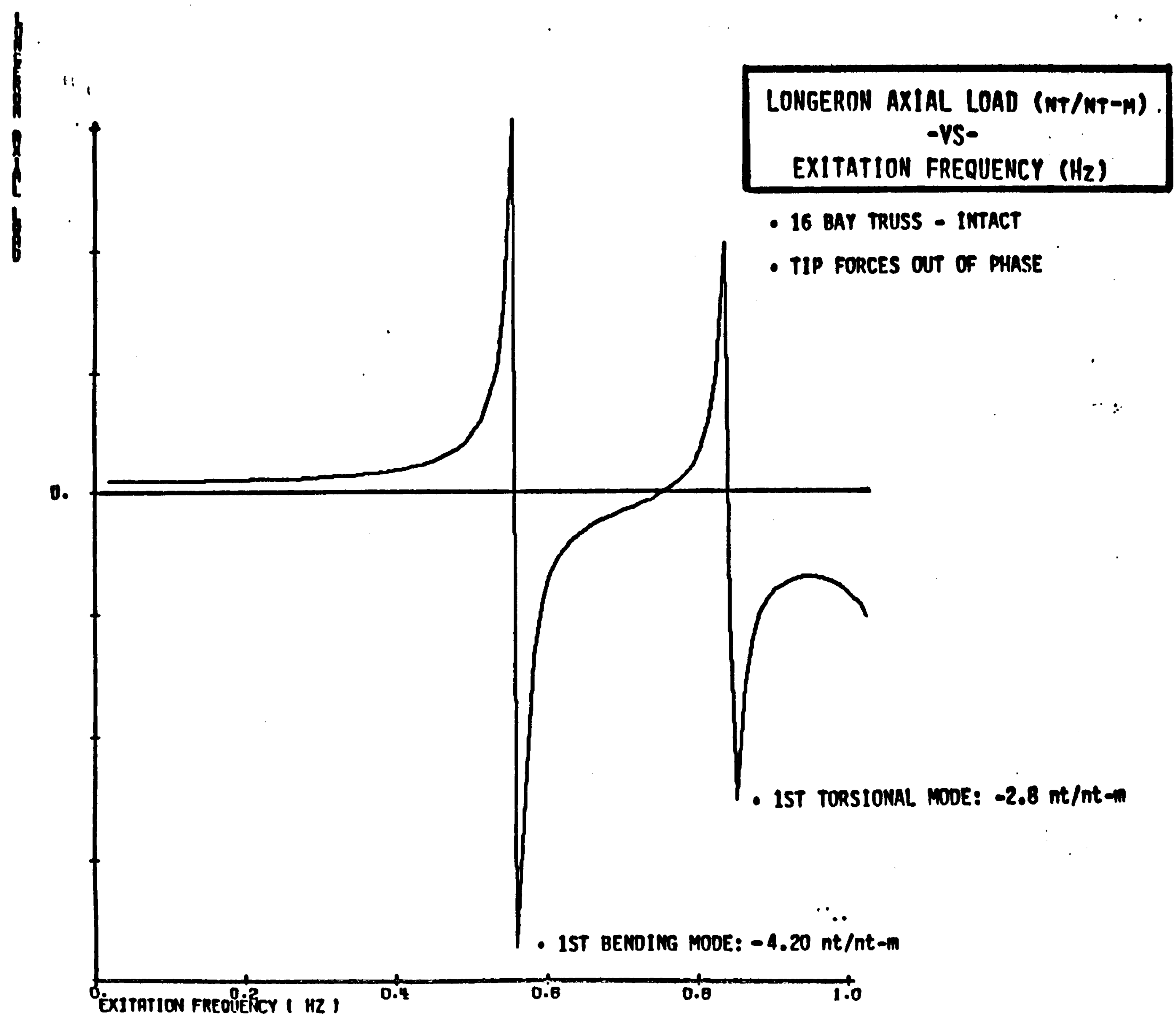
SINUSOIDAL RESPONSE ANALYSIS
(FORCES OUT OF PHASE)

		F (Hz)	+Y TIP RESPONSE MAX. DISP. cm/nt-m	+Y TIP RESPONSE MAX. ACC. $(m/s^2)/nt\text{-}m$	-Y TIP RESPONSE MAX. DISP. cm/nt-m	-Y TIP RESPONSE MAX. ACC. $(m/s^2)/nt\text{-}m$	MAX. MEMBER LOAD AT BASE nt/nt-m
MODE #1 1ST BENDING	TRUSS INTACT	0.5594	0.0051	0.0006	0.0097	0.0012	- 4.20
	LONGERON REMOVED	0.5026	0.0032	0.0032	0.0055	0.0005	- 4.42
	BATTEN REMOVED	0.5529	0.0043	0.0005	0.0115	0.0014	- 6.56
	DIAGONAL REMOVED	0.5510	0.0058	0.0007	0.0146	0.0017	- 3.87
MODE #2 1ST TORSION	TRUSS INTACT	0.8482	0.0205	0.0057	0.0154	0.0043	- 6.30
	LONGERON REMOVED	0.8093	0.0144	0.0036	0.0147	0.0037	- 10.96
	BATTEN REMOVED	0.8187	0.0247	0.006	0.0167	0.0043	- 8.85
	DIAGONAL REMOVED	0.8202	0.2292	0.006	0.0153	0.004	- 7.66

THIS FIGURE SHOWS THE STEADY STATE ACCELERATION RESPONSE FOR TIP FORCES 180 DEGREES OUT OF PHASE. NOTE THAT THE OUT OF PHASE FORCES EXCITED THE TORSIONAL MODE MORE EFFECTIVELY THAN DID THE IN PHASE FORCES.


X, Y & Z ACCELERATIONS
OF +Y TIP $(m/s^2)/(NT\text{-}M)$
-VS-
EXITATION FREQUENCY (Hz)
• 16 BAY TRUSS - INTACT
• TIP FORCES OUT OF PHASE
• 1ST TORSIONAL MODE: 0.0057 $(m/s^2)/nt\text{-}m$
• 1ST BENDING MODE: 0.0006 $(m/s^2)/nt\text{-}m$
X • Y + Z ACCELERATIONS +Y TIP
0.
0.
0.2
0.4
0.6
0.8
1.0
EXITATION FREQUENCY (HZ)

THIS FIGURE SHOWS THE STEADY STATE LONGERON LOADS FOR THE TIP FORCES 180 DEGREES OUT OF PHASE.


LONGERON AXIAL LOAD (NT/NT-M)
-VS-
EXITATION FREQUENCY (Hz)
• 16 BAY TRUSS - INTACT
• TIP FORCES OUT OF PHASE
• 1ST TORSIONAL MODE: -2.8 nt/nt-m
• 1ST BENDING MODE: -4.20 nt/nt-m
0.
0.2
0.4
0.6
0.8
1.0
EXITATION FREQUENCY (HZ)

A PRELIMINARY EVALUATION OF PRIMARY RCS FIRING CONSTITUES THE REMAINDER OF THIS STUDY. ASSUMING FAILURE OF THE VERNIER SYSTEM IT IS DESIRABLE TO UNDERSTAND THE CONSTRAINTS, IF ANY, WHICH MUST BE IMPOSED UPON USE OF THE PRIMARY RCS JETS.

THREE MANEUVERS WERE CONSIDERED: ROLL, PITCH, AND YAW AS OUTLINED ON THIS CHART.

THE MAXIMUM NUMBER OF JETS AVAILABLE FOR EACH MANEUVER WERE USED BUT WERE FIRED IN A SINGLE, 80 MS PULSE. REPEATED PULSES, PARTICULARLY AT A NATURAL FREQUENCY OF THE STRUCTURE, COULD IMPOSE MORE SEVERE STRUCTURAL LOADS.

PRCS FIRING RESPONSE ANALYSIS

- ROLL MANEUVER: JETS FIRED WERE R1u L2D
R2u L3D
R4u L4D

  TOTAL ROLL TORQUE = 5.775×10^4 nt-m (4.259×10^4 ft-lbf)

- PITCH MANEUVER: JETS FIRED WERE F1D L1u R1u
F2D L2u R2u
F3D L3u R4u
F4D

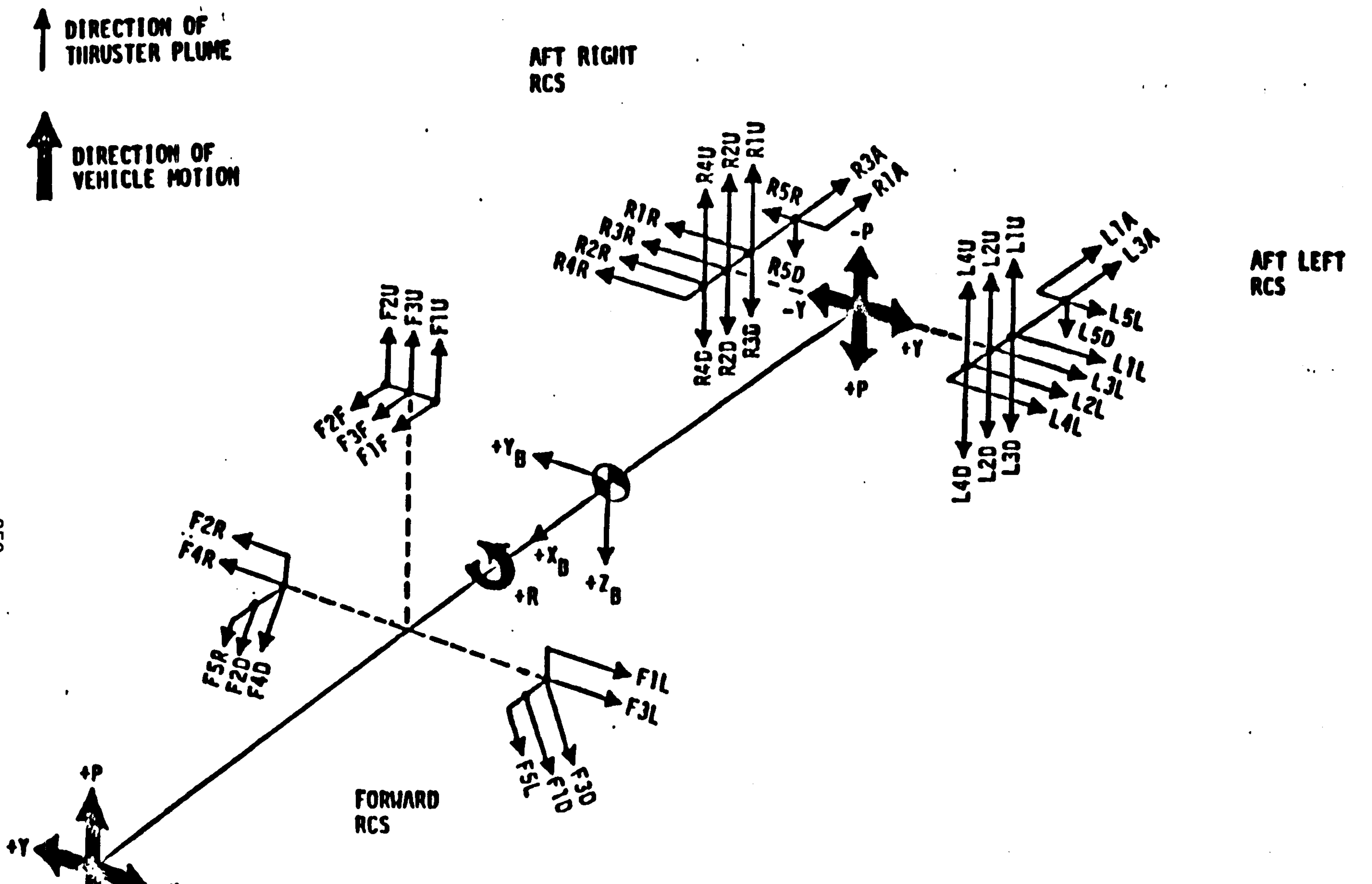
  TOTAL PITCH TORQUE = 4.282×10^5 nt-m (3.158×10^5 ft-lbf)

- YAW MANEUVER: JETS FIRED WERE F2R L1L L3L
F4R L2L L4L

  TOTAL YAW TORQUE = -3.1423×10^5 nt-m (-2.317×10^5 ft-lbf)

- EACH MANEUVER = ONE 80 MS PULSE OF ALL JETS
- EXPERIMENT FIXTURE STIFFNESS
- STRUCTURAL DAMPING RATIO = 1/2%
- 8 BAYS W/O TRAYS & 16 BAYS W/TRAYS

THE VERNIER AND PRIMARY RCS JET LOCATIONS ARE SHOWN ON THIS FIGURE.



RCS JET LOCATIONS

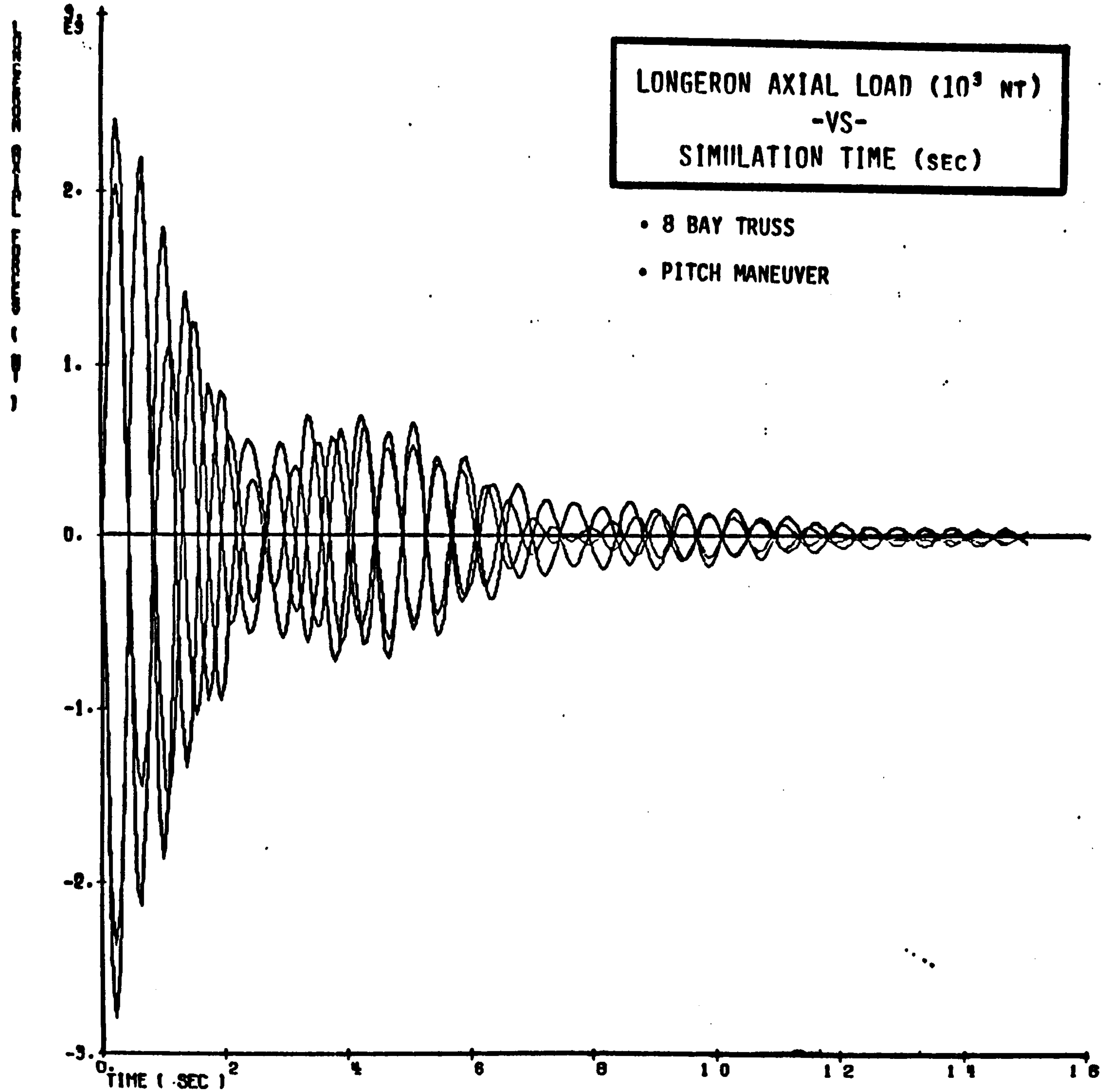
THE RESULTS OF PRCS FIRING ARE SHOWN IN THIS TABLE FOR THE 8 BAY CONFIGURATION. NOTE THAT THE PITCH MANEUVER PRODUCED THE HIGHEST MEMBER LOADS, BUT THE COMPRESSION LOADS REMAINED WELL BELOW THE CALCULATED LONGERON BUCKLING LOAD OF ABOUT 1700LBS. ROTATIONAL ACCELERATIONS WERE ALL BELOW 1 DEG/S**2.

SUMMARY OF PRCS FIRING RESPONSE ANALYSIS

(8 BAYS)

	ROLL	PITCH	YAW
MAX. COMPRESSIVE LOAD AT BASE	-1445.1 nt (-324.9 lbf)	-2782.0 nt (-625.4 lbf)	-866.7 nt (-194.8 lbf)
MAX. TENSILE LOAD AT BASE	1463.9 nt (329.1 lbf)	2391.4 nt (537.6 lbf)	817.3 nt (183.7 lbf)
MAX. ROTATIONAL ACCELERATION OF SHUTTLE C.G.	0.719 deg/s^2	0.885 deg/s^2	-0.568 deg/s^2

THE TRANSIENT LONGERON AXIAL LOAD FOR THE 8 BAY CONFIGURATION IN PITCH IS SHOWN ON THIS FIGURE. NOTE THAT MODAL DAMPING OF 0.5% WAS USED IN THE CALCULATION.


LONGERON AXIAL LOAD (10^3 NT)
-VS-
SIMIILATION TIME (SEC)
• 8 BAY TRUSS
• PITCH MANEUVER
E3
2.
1.
0.
-1.
-2.
-3.
0
2
4
6
8
10
12
14
16
TIME (SEC)

THE RESPONSES FOR THE 16 BAY CONFIGURATION ARE SHOWN IN THIS TABLE.

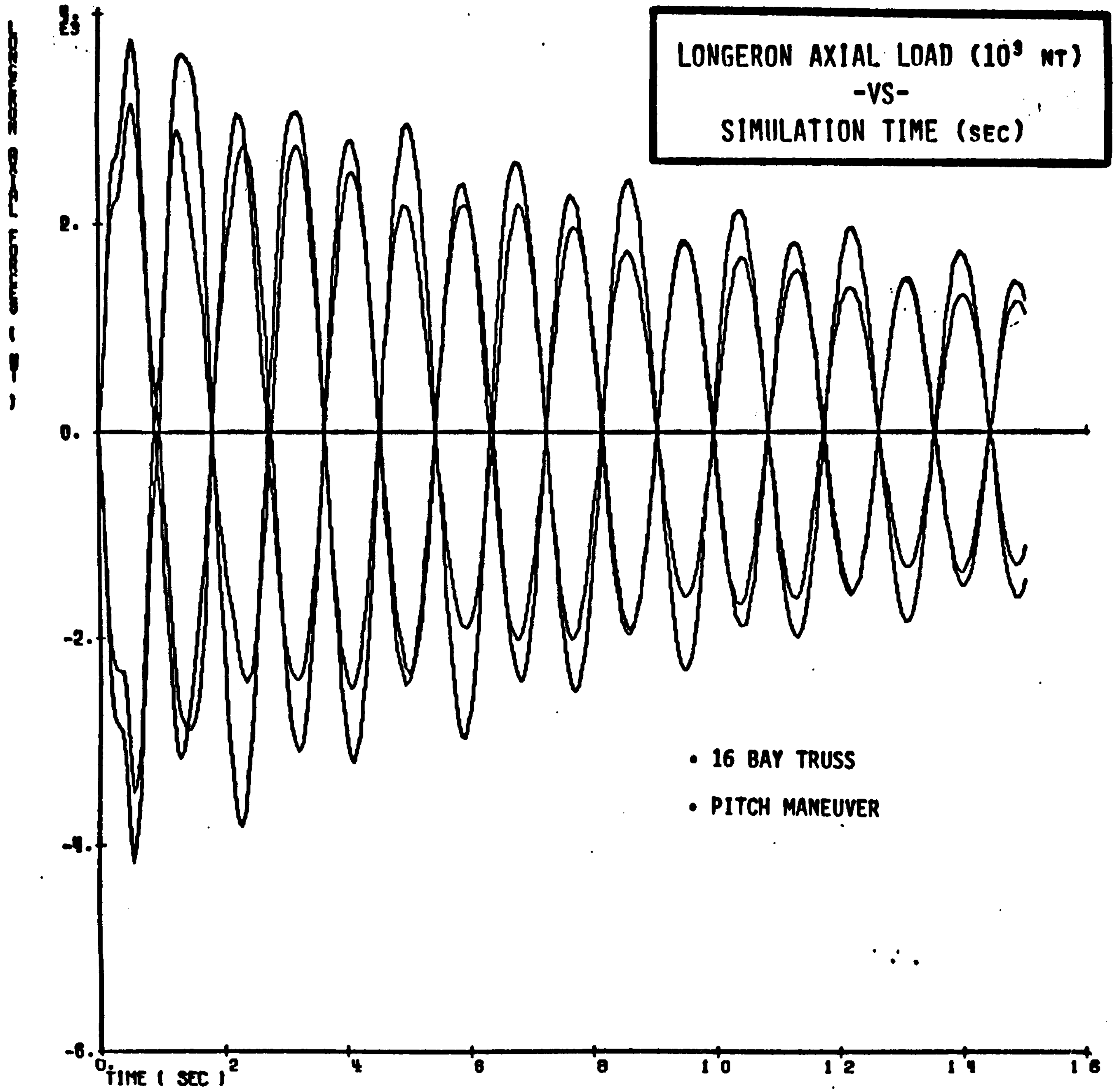
THE PITCH MANEUVER AGAIN RESULTED IN THE LARGEST MEMBER LOADS, BUT IN THIS CASE THE MAXIMUM LOAD WAS MORE THAN HALF OF THE BUCKLING LOAD.

SUMMARY OF PRCS FIRING RESPONSE ANALYSIS

(16 BAYS)

	ROLL	PITCH	YAW
MAX. COMPRESSIVE LOAD AT BASE	-1511.7 nt (-339.8 lbf)	-4156.0 nt (-934.3 lbf)	-871.8 nt (-196.8 lbf)
MAX. TENSILE LOAD AT BASE	1494.3 nt (335.9 lbf)	3743.5 nt (841.6 lbf)	834.3 nt (187.6 lbf)
MAX. ROTATIONAL ACCELERATION OF SHUTTLE C.G.	0.702 deg/s^2	0.875 deg/s^2	-0.568 deg/s^2

THE TRANSIENT LONGERON AXIAL LOADS FOR THE 16 BAY CONFIGURATION IN THE PITCH MANEUVER IS SHOWN ON THIS FIGURE.


LONGERON AXIAL LOAD (10^3 NT)
-VS-
SIMULATION TIME (SEC)
• 16 BAY TRUSS
• PITCH MANEUVER
TIME (SEC)
0.
2.
-2.
-4.
-6.
2
4
6
8
10
12
14
16

THE 16 BAY CONFIGURATION THAT WAS ANALYZED POSSESSES 1ST NATURAL FREQUENCIES IN BENDING AND TORSION OF 0.5594 HZ AND 0.8482 HZ RESPECTIVELY. (ATTACHED TO THE ORBITER THROUGH THE EXPERIMENT ATTACHMENT FIXTURE).

SINUSOIDAL ANALYSIS CAN BE USED TO CONFIGURE THE EXCITATION AND TRANSDUCER SYSTEMS AND TO DETERMINE ON ORBIT DAMPING FROM POST FLIGHT DATA INTERPRETATION USING SYSTEM IDENTIFICATION TECHNIQUES. THE MEMBER OUT DATA WILL PROVIDE DIFFERENT BOUNDARY CONDITIONS TO BE USED IN ISOLATING THE SAVE SUBSTRUCTURE FROM THE TOTAL SYSTEM.

REALISTIC PRCS FIRING SCENARIOS SHOULD BE DEVISED WHICH CAN BE TOLERATED DURING CONSTRUCTION AND IN THE FINAL ASSEMBLED CONFIGURATION. REQUIRED OPERATIONAL CONSTRAINTS, IF ANY, SHOULD BE DEVELOPED.

CONCLUSIONS

- Desired 1st Bending And 1st Torsional Frequencies Appear To Be Achievable.
  - Attachment Fixture Stiffness Must Be 1×10^{7} nt/m Or Greater
  - Trays Positioned Near Orbiter Have Negligible Effect On 1st Bending And 1st Torsional Frequencies
- Sinusoidal Analysis Should Be Used To Guide Experiment Design
  - Force Amplitude/Sweep Rate
  - Transducer Selection, Placement, And Amplitude And Frequency Ranges
- PRCS Firing Is Possible Without Breaking Structure. However, Operational Constraints Should Be Required For Other Firing Scenarios.

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SECTION III

Langley Research Center Free Flyer Analysis Study

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STRUCTURAL ASSEMBLY VERIFICATION EXPERIMENT
(SAVE)

FREE FLIGHT MODE CONFIGURATION ANALYSIS
FINAL REPORT

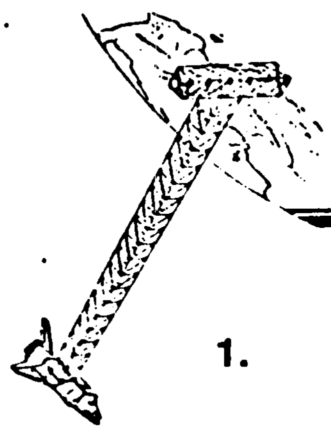
JUNE 4-6, 1986

L. J. DeRYDER, LaRC SSO
B. P. ROBERTSON, PRC KENTRON
J. T. COLEMAN, BOEING AC

ANALYSIS TASKS

Five analysis tasks were performed to assess the Free Flight mode characteristics and requirements for separating and leaving in low earth orbit the SAVE truss structure configuration. Initially, three configurations were conceived and analytical geometry computer math models were created to synthesize the physical characteristics of each concept. The key parameters derived for each configuration concept included configuration mass properties, inertia matrices, aerodynamic drag areas and offset distances between each configuration's center of gravity and center of aerodynamic pressure. These derived physical characteristics permitted assessments to be made of each configuration's ballistic coefficient, aerodynamic drag and orbital decay rate to determine if the 3-year orbital lifetime mission goal could be achieved. These physical configuration characteristics were also used to determine the orbital flight mode stability and attitude control requirements for various attitude orientations to enhance drag rates and assembly construction schemes.

When initial investigations indicated that a 3-year orbital lifetime could not be achieved without an orbital altitude reboost capability, a final task was levied to derive spacecraft utility bus options, synthesize their physical size characteristics, and estimate cost levels for each option derived.



ANALYSIS TASKS

1. CONFIGURATION SYNTHESIS OF DEFINED CONCEPTS
   - 3 CONFIGURATION OPTIONS STUDIED

2. DERIVATION OF PHYSICAL CHARACTERISTICS
   - MASS, INTERTIA, DRAG AREAS, CG/CP OFFSET
   - UTILITY TRAY CONFIGURATION CHARACTERIZATION

3. ORBITAL DECAY RATE/LIFETIME ASSESSMENT
   - BALLISTIC COEFFICIENT, DECAY RATE, DRAG MAKE-UP COMPARISIONS

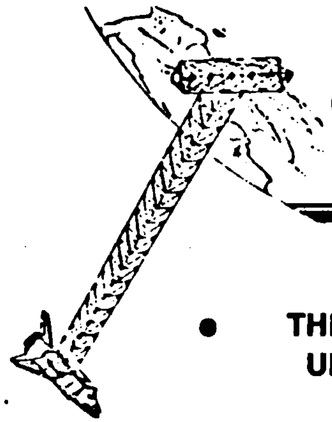
4. FREE FLIGHT MODE STABILITY AND CONTROL DETERMINATION
   - STABILITY / CONTROLLABILITY AND ATTITUDE ORIENTATION

5. SPACECRAFT UTILITY BUS SYNTHESIZATION AND COST MODEL DETERMINATION
   - FOUR UTILITY BUS OPTIONS ASSESSED

CONFIGURATION OPTIONS STUDY REVIEW SUMMARY

Three 20 bay 5 meter truss configurations, each 100 meters in length, were assessed for uncontrolled free flight stability and orbital decay rate characteristics. As will be described in pages to follow, these configurations were known as the "I," "T," and "L" configurations which indicated their physical appearance. Ballistic coefficient trade studies were performed to evaluate the effect of inclusion or non-inclusion of utility tray concepts that would duplicate the wiring cable and fluid line runs expected in the actual Space Station structure build-up. Two utility tray run concepts were assessed for flight assembly verification versus structural dynamic testing considerations. One was a full 100 meter dual tray run and the other only a 50 meter dual tray run. Based upon initial configuration assessments, a candidate 20 bay configuration was selected for structural characterization and assembly verification. For this candidate configuration several flight mode orientation trade-off assessments and stability/controllability characterizations were made. A spacecraft utility bus was baselined, sized and considered in these analysis for impact assessment.

These studies were repeated when a 16 bay (80 meter) truss configuration with 40 meter long dual utility trays was chosen as the final design candidate. Four spacecraft bus options were generated for this final configuration with cost being the primary option driver. An orbital reboost maneuver strategy was assessed for spacecraft bus propellant sizing.



CONFIGURATION OPTIONS STUDY REVIEW SUMMARY

- THREE INITIAL 20 BAY (100 METER) TRUSS CONFIGURATIONS ASSESSED FOR UNCONTROLLED FREE FLIGHT STABILITY AND ORBIT DECAY CHARACTERISTICS
  - BALLISTIC COEFFICIENT TRADE STUDY PERFORMED WITH AND WITHOUT UTILITY TRAYS

- CANDIDATE 20 BAY (100 METER) CONFIGURATION SELECTED FOR STRUCTURAL CHARACTERIZATION AND ASSEMBLY BASELINE
  - 2 UTILITY TRAY OPTIONS ASSESSESD

    1. ONE 100 METER DUAL UTILITY TRAY RUN
    2. TWO 50 METER DUAL UTILITY TRAY RUNS

  - FLIGHT MODE ATTITUDE ORIENTATION TRADES PERFORMED
  - SPACECRAFT UTILTY BUS SIZED AND CONSIDERED IN FLIGHT ANALYSIS

- REVISED 16 BAY (80 meter) TRUSS CONFIGURATION WITH DUAL UTILITY TRAYS ANALYSED
  - FLIGHT MODE STABILITY, CONTROL AND REBOOST MANEUVER ASSESSMENTS PERFORMED
  - FOUR SPACECRAFT BUS OPTIONS IDENTIFIED AND ASSESSED

FINAL REPORT TOPICS

This final report contains a review of the configuration options traded off and a description of the spacecraft models generated for size and cost assessments. The flight mode orientation, stability, controllability and orbital decay/reboost requirements are presented for the 80 meter SAVE design concept settled upon by this Phase A study. Finally, spacecraft bus options trade-off assessments are presented.

(Note: These spacecraft options assessment are presented in section one of this report.)

FINAL REPORT TOPICS

- REVIEW OF CONFIGURATION OPTIONS AND SPACECRAFT COST MODELS
- 80 METER "T" BASELINE CONCEPT REVIEW
- SPACECRAFT BUS OPTION ASSESSMENT

CANDIDATE TRUSS CONFIGURATIONS
PHYSICAL CHARACTERISTICS

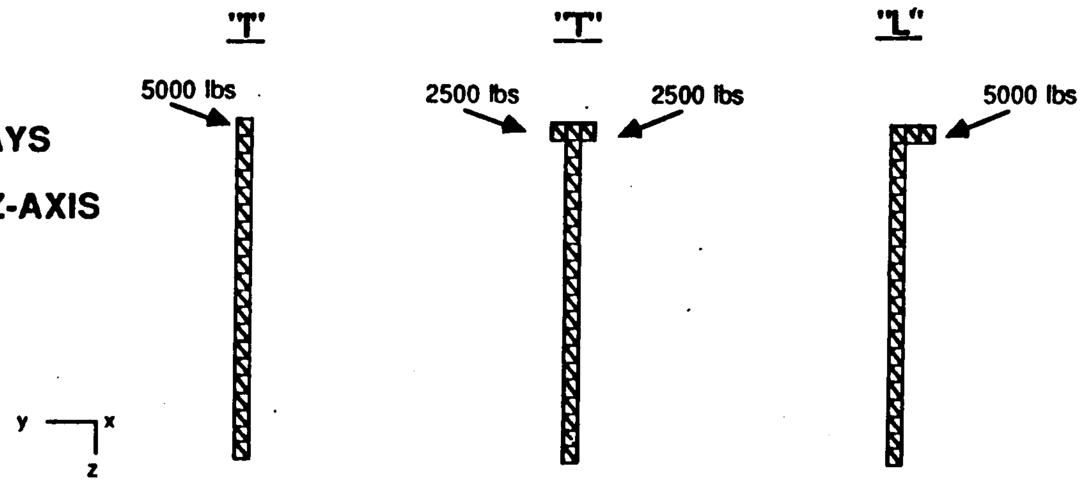
The physical characteristics of the initial SAVE truss candidate configurations were derived for consideration of either leaving the experiment dependent tip mass on orbit or removing it. All configurations without tip mass, while showing a strong principal axis inertia characteristic did upon inspection reveal small inertia cross products due to the arrangement of the diagonal strut members. The "L" configuration exhibited a large Iyz characteristic which is a forecast of potential orbital orientation instability due to induced gravity gradient torques. For the "L" configuration, this Iyz term becomes totally unacceptable for free flight stability considerations when the tip mass is present. The relationship between principal inertias and inertia cross products appear fairly insensitive to the presence or absence of tip mass for the "I" or "T" configurations.

The aerodynamic drag area of 60 to 66 square meters computed for the worst case unblocked truss condition which would be the expected case for a structure with this large overall dimension and small truss strut dimension in the orbital rarified gas flow condition considered. This is a relatively large drag area with respect to the synthesized configuration mass and is a forecast of relatively low ballistic coefficients than that desired for a low earth orbit Shuttle compatible mission altitude.

The center of gravity offset displacement between the no tip mass and tip mass present configurations is also a forecast that orbital flight mode body torques will be generated by aerodynamic drag forces.

CANDIDATE TRUSS CONFIGURATIONS PHYSICAL CHARACTERISTICS

- 20 5 METER VERTICAL BAYS
- 100 METER Z-AXIS LENGTH



Configuration	ZERO TIP MASS "I"	ZERO TIP MASS "L"	ZERO TIP MASS "T"	5000 LBS TIP MASS "I"	5000 LBS TIP MASS "L"	5000 LBS TIP MASS "T"
Mass (kg)	1280	1408	1408	3548	3676	3676
Inertia (kg M^2)						
Ixx	1.34E6	1.61E6	1.36E6	2.07E6	2.57E6	3.35E6
Iyy	1.34E6	1.49E6	1.36E6	2.07E6	3.22E6	3.22E6
Izz	12800	21400	17300	12800	1.43E5	1.45E5
Ixy	-321	-354	-354	-321	-354	-354
Ixz	-612	-673	-673	-612	-673	-673
Iyz	612	-40800	-673	612	-4.84E5	-673
Drag Area (M^2)	60	66	66	60	66	66
CG - CP Offset (M)	0	0.27	0.27	32.0	28.1	26.9

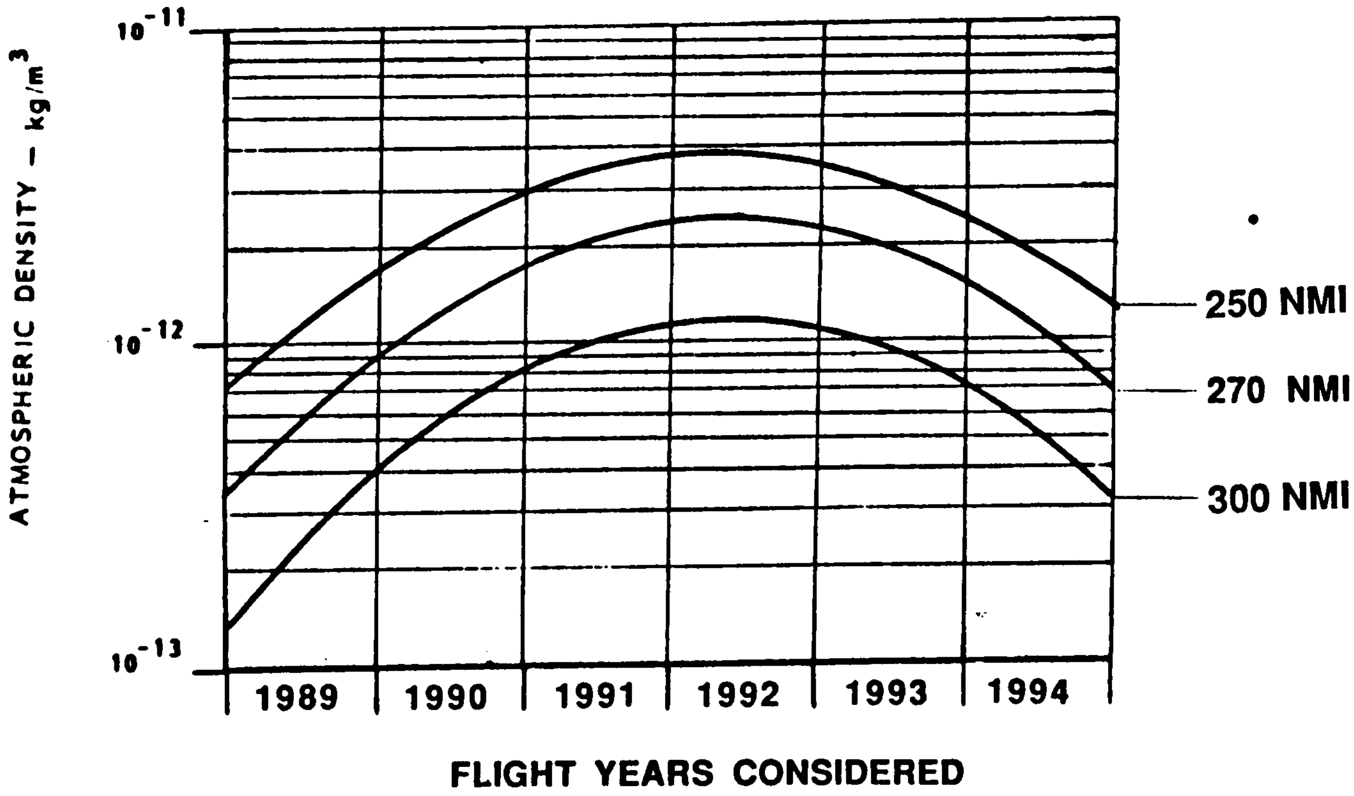
ATMOSPHERIC DENSITY PROFILE

The yearly solar radiation predictions for the proposed SAVE mission years 1989 thru 1992 being considered show an increasing atmospheric density profile can be expected. Based upon the 11 year cyclic predictions obtained from NASA TM-82585, the maximum atmospheric density would be expected to occur in the third year of the SAVE mission.

ATMOSPHERIC DENSITY PROFILE

REF: NASA TM-82585 (MSFC JULY 1984)

- PEAK SOLAR ACTIVITY PREDICTED FOR PROPOSED 1989- 1992 SAVE MISSION
  - MAXIMUM ATMOSPHERIC DENSITY OCCURS IN 3RD MISSION YEAR

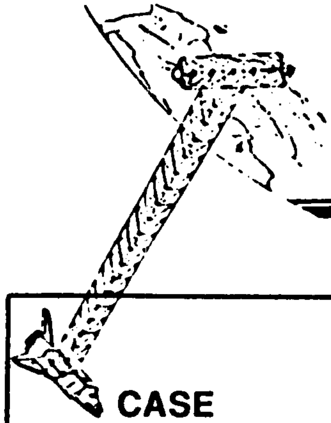


ORBITAL LIFETIMES FOR VARIOUS TRUSS SCENARIOS

Orbital lifetimes for various SAVE truss scenarios indicate low ballistic coefficients and small orbit lifetimes can be expected. For the truss geometry dimensions under consideration, total tip mass weight of 5000 pounds would only yield an expected orbital lifetime of one year.
To obtain a 3 year orbital lifetime 46,000 pounds would have to be considered for total tip mass at an initial altitude of 270 nautical miles and 86,000 pounds for 250 nautical mile initial altitude. This of course is out of the Shuttle performance altitude/payload manifesting consideration range.

For comparison, flight mode orientations are shown in the "horizontal" attitude where the length of the truss configuration, or z axis, is along the orbital flight path vector. Vertical orientation assumes the z-axis is perpendicular to the flight path and aligned to earth Nadir. Horizontal flight mode yields no beneficial performance.

Utility tray considerations representative of the "baseline" Space Station initial and growth configurations indicates no beneficial effect of increased ballistic coefficient over the 5000 pound tip mass configuration option whose ballistic coefficient is calculated to be 26. This is due to the large increase in drag area in either the "feathered" (edge to the flight path) or the unfeathered tray orientation which overshadows the effect of increased weight.



ORBITAL LIFETIMES FOR VARIOUS TRUSS SCENARIOS

CASE	ORIENTATION	BALLISTIC COEFFICIENT	TIME FOR 270-220 NM ORBIT DECAY	TIME FOR 250-220 NM ORBIT DECAY
NO TIP MASS	VERTICAL	9	170 DAYS	80 DAYS
1000 LB TIP MASS	VERTICAL	13	210 DAYS	100 DAYS
5000 LB TIP MASS	VERTICAL	26	1 YEAR	200 DAYS
26,000 LB TIP MASS	VERTICAL	95	2.3 YEARS	1.5 YEARS
46,000 LB TIP MASS	VERTICAL	160	3 YEARS	2 YEARS
86,000 LB TIP MASS	VERTICAL	292	6 YEARS	3 YEARS
NO TIP MASS	HORIZONTAL	13	210 DAYS	100 DAYS
5000 LB TIP MASS	HORIZONTAL	39	490 DAYS	260 DAYS

UTILITY TRAY BALLISTIC CHARACTERISTICS

CONFIGURATION	UTILITY TRAY MASS (kg)	UTILITY TRAY AREA (M^2)	BALLISTIC COEFF. OF TRUSS WITH UTILITY TRAYS (Kg/M^2)	BALLISTIC COEFF. OF TRUSS WITHOUT UTILITY TRAYS (Kg/M^2)
"BASELINE" UTILITY TRAY	6,300	170 (10)	8 (28)	13
"GROWTH" UTILITY TRAY	12,600	340 (20)	8 (39)	13

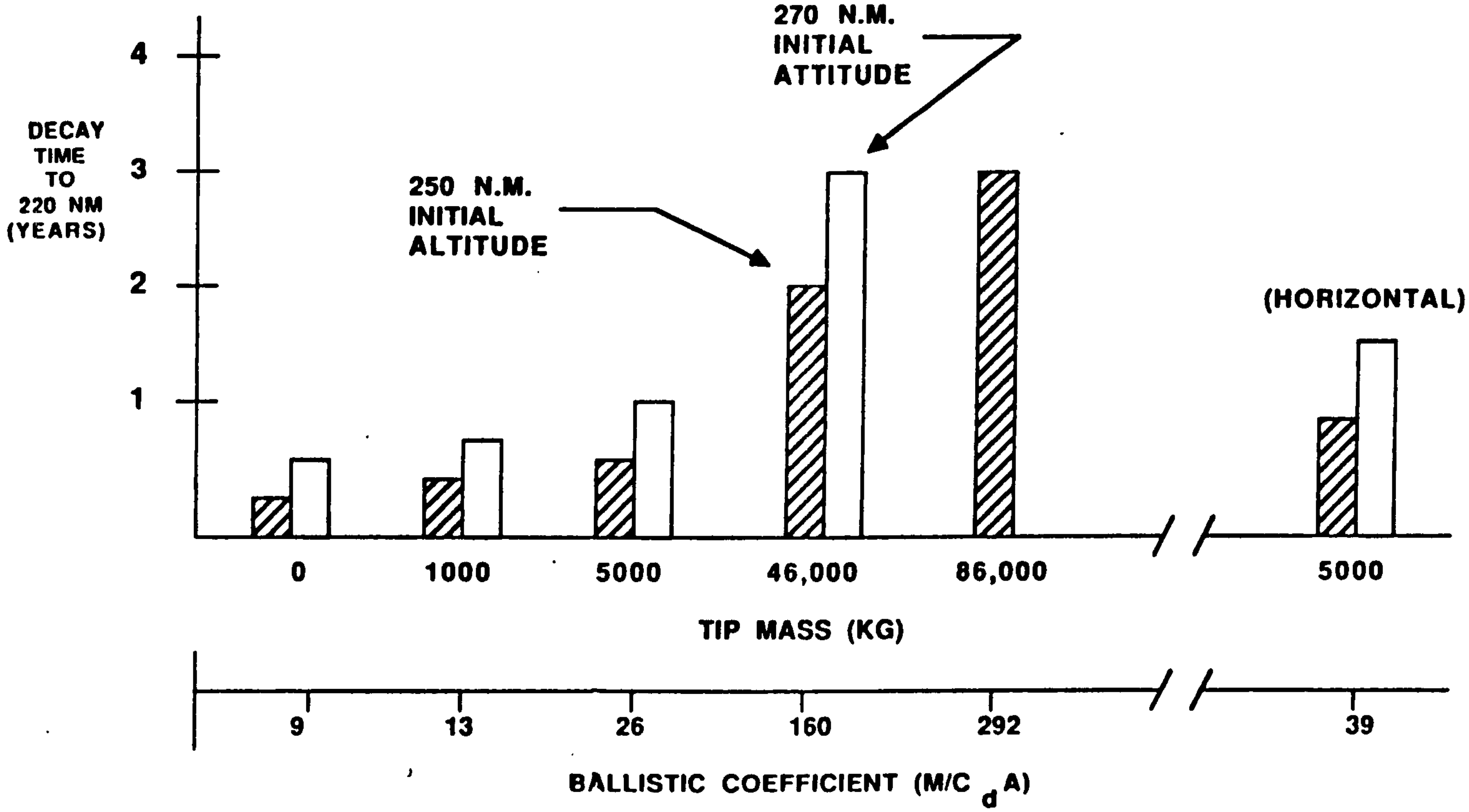
( ) = EDGE ON "FEATHERED"

ORBIT LIFETIME PROFILES FOR 20 BAY "I" TRUSS

Using the "I" truss as the comparison example with a ballistic coefficient of 26, it is seen that an altitude of about 270 nautical miles minimum should be considered for deploying the SAVE truss on orbit. While 270 nautical miles only achieves 30 percent of the desired 3 year lifetime objective, and requires an orbital reboost capability to be considered, it is a better choice than a 250 nautical mile initial altitude. At 250 nautical miles, a 5000 pound total tip mass yields only about a 6 month orbital lifetime which would require twice the orbital reboost requirements of a 270 nautical mile minimum initial altitude.

ORBIT LIFETIME PROFILES FOR 20 BAY "I" TRUSS

(ASSUMES 4-1-89 LAUNCH WITH 2 σ ATMS, CD = 2.3)

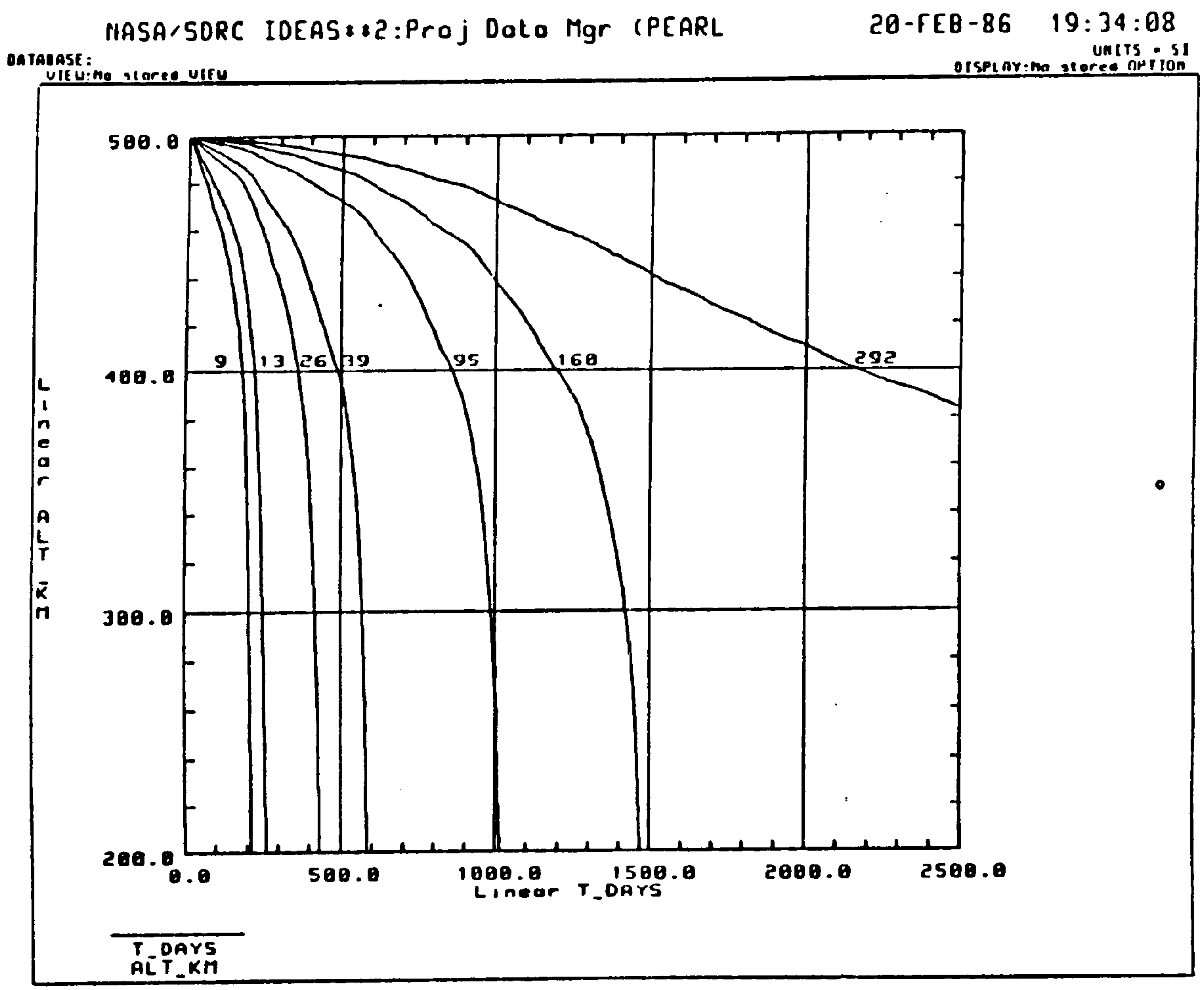


ORBIT DECAY AS A FUNCTION OF BALLISTIC COEFFICIENT (500 KM INITIAL ALTITUDE)

Decay rate profiles for 270 nautical miles (500 Kilometers) and 250 nautical miles (463 Kilometers) for various ballistic coefficient considerations are presented to indicate the decay rate characteristics that drive the consideration of a 270 nautical mile minimum altitude choice for reboost strategy formulation and sizing.

This diagram shows decay rate profiles starting at 270 nautical miles (500 Kilometers). Altitudes below 220 nautical miles (400 kilometers) show very high decay rates indicating the lowest orbital altitude limit at which to initiate a reboost maneuver.

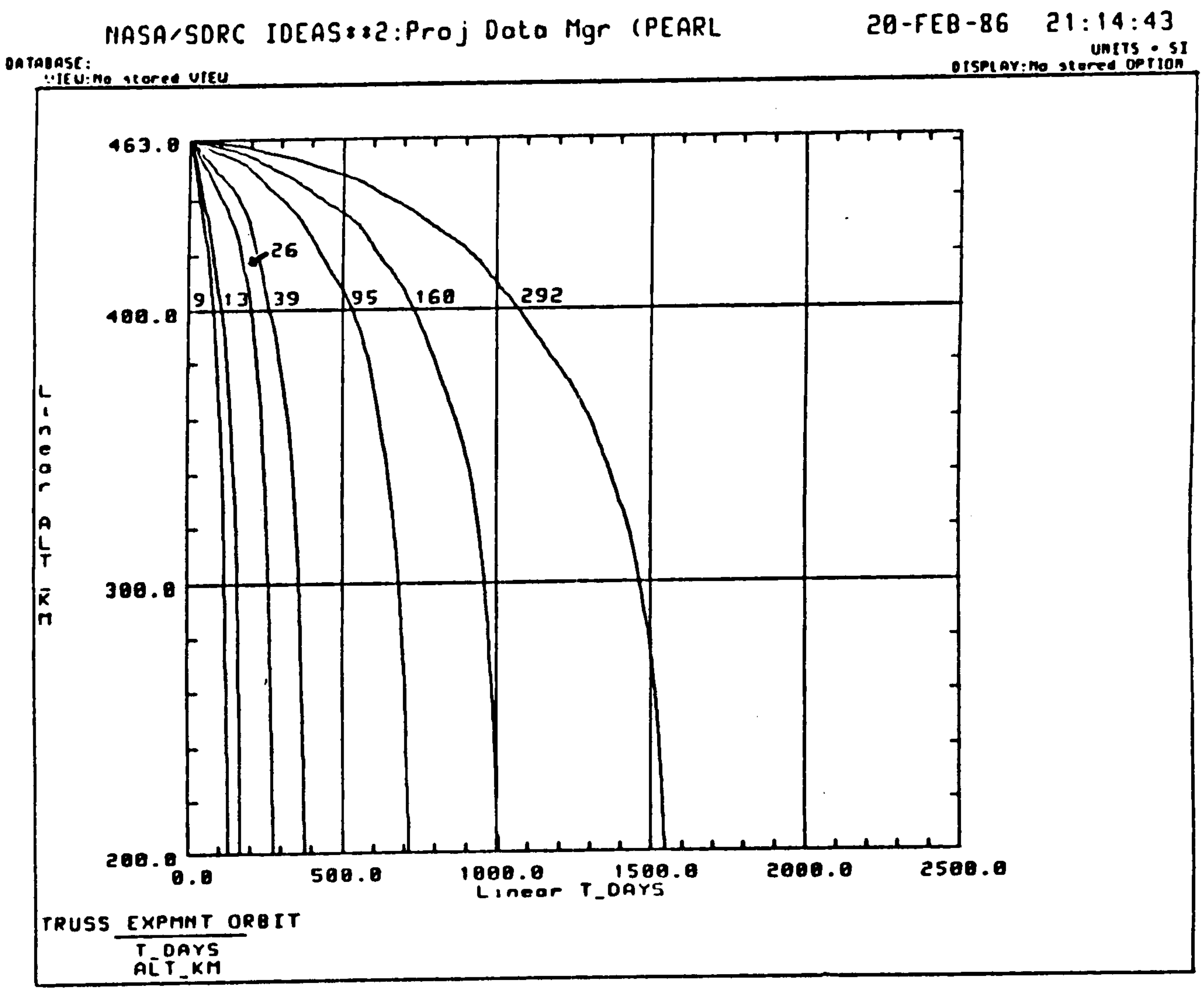
Orbit decay as a function of ballistic coefficient (500 km initial altitude)



ORBIT DECAY AS A FUNCTION OF BALLISTIC COEFFICIENT (463 KM INITIAL ALTITUDE)

The plot for a 250 nautical mile (463 Kilometer) initial orbital altitude shows decay rates for ballistic coefficients between 9 and 39 to be twice as high as for 270 nautical miles (500 Kilometers). Ballistic coefficients between 9 and 39 are the range to be expected for SAVE truss configurations under consideration.

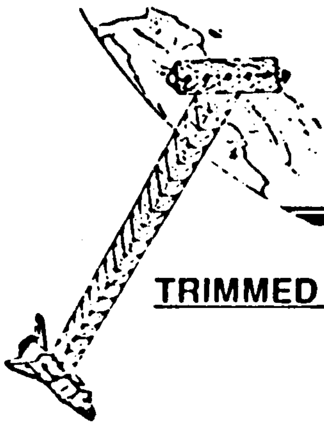
Orbit decay as a function of ballistic coefficient (463 km initial altitude)



PITCH CHANNEL CONTROLLER IS DOMINANT REQUIREMENT WITH TIP MASS PRESENT

As previously pointed out all three initial configuration geometries had large center of gravity displacements from the center of aerodynamic pressure of 32 meters for the "I" configuration, 28 meters for the "L" configuration and 27 meters for the "T" configurations when tip masses were left attached for orbital free flight. This causes the aerodynamic forces to exert cyclic torques on the pitch channel when oriented with the z axis aligned with earth Nadir (LV/LH). As has been shown, the horizontal altitude (i.e., z axis aligned to the flight path) offers no aerodynamic drag advantage and will be shown later to exhibit unstable attitude stability characteristics.

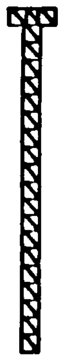
The aerodynamic torques generated by the large cg/cp offsets are the dominant factor for the cyclic pitch channel control force characteristics shown for "T" configuration geometry depicted as a function of angular position in the orbit. As shown, the orbit position varies from 0 to 360 degrees. Because all three configurations had cg/cp offsets in the range of 27 to 32 meters, all three configurations exhibited the same characteristic of pitch channel control being the dominant requirement with tip mass present.

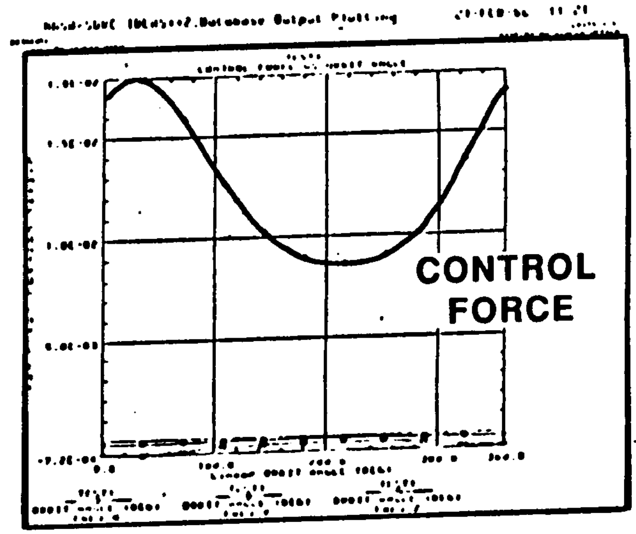


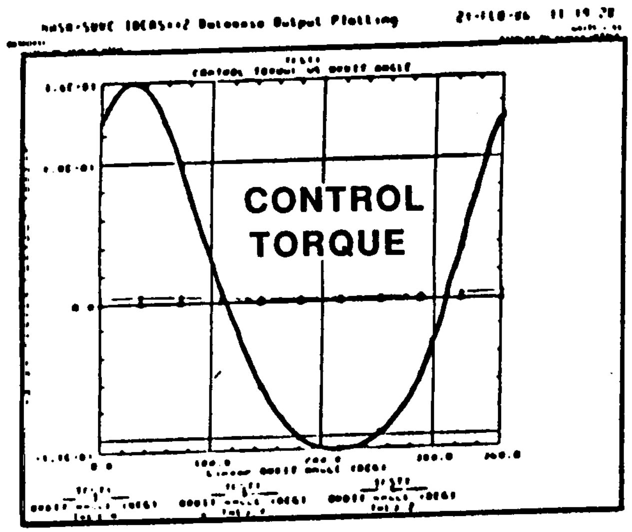
PITCH CHANNEL CONTROLLER IS DOMINANT REQUIREMENT WITH TIP MASS PRESENT

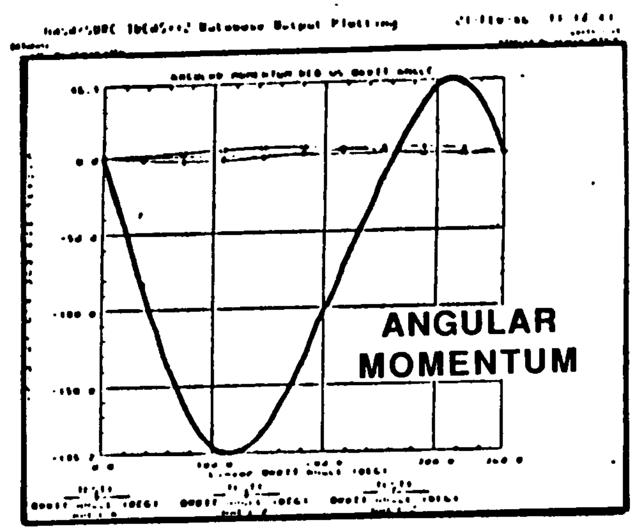
TRIMMED "T" WITH 5000 LB TIP MASS

T CONFIGURATION









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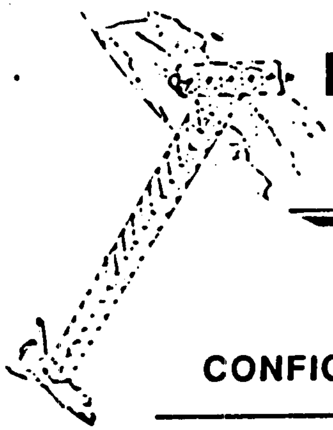
LONG TERM STABILITY CHARACTERISTICS REQUIRE REBOOST POINTING CONTROL

The inertia property characteristics of the three initial configurations studied as shown earlier are such that the roll axis inertias (Ixx) are either closely equal to the pitch axis inertia (Iyy) for the "I" and "T" configurations or I_{roll} greater than I_{pitch} for the "L" configuration. All three configurations had relatively small Izz (yaw) axis principal inertias. For altitude stability considerations, this yields an unstable yaw equilibrium characteristic that is dominant for configurations considered. As shown without tip masses present, yaw position errors can vary up to 90 degrees over a 5 orbit observation period. For the case of tip mass left attached to the structure, the aerodynamic forces due to cg/cp offset, as previously discussed, cause an altitude position error of up to 10 degrees peak over the same 5 orbit observation period to be expected.

The observed peak attitude error rates were observed to be small for all orientations analized and would not be expected to cause concern for future orbital rendezvous with the Shuttle or astronaut extravehicular activity (EVA). However, because of the need for reboost within a year, as previously discussed, the need exists for body axis position control to maintain thrust vector alignment for orbit altitude adjust maneuvers.

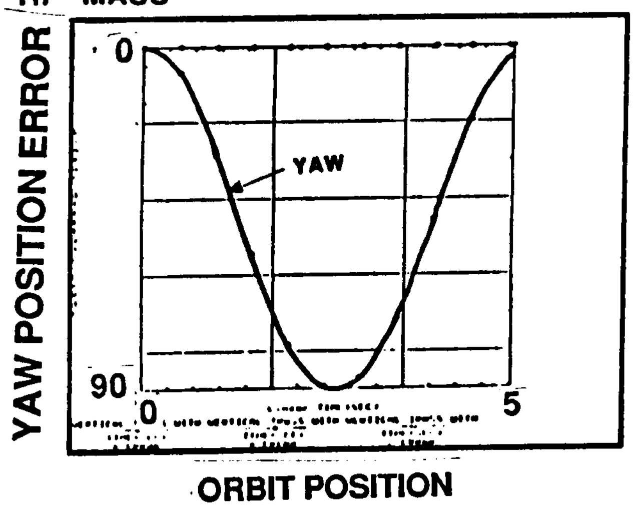


LONG TERM STABILITY CHARACTERISTICS REQUIRE REBOOST POINTING CONTROL

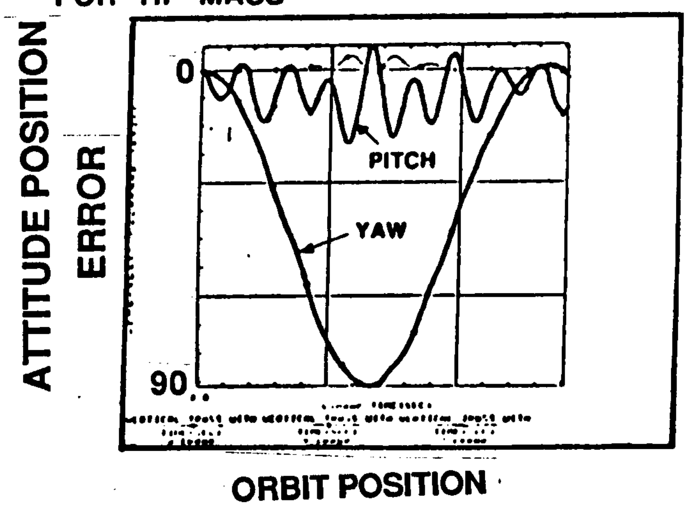
ATTITUDE ERROR PEAK ANGULAR RATES

CONFIGURATION	TIP MASS (LBS)	INITIAL ORIENTATION	PEAK ANG. RATE (DEG/SEC) X	Y	Z
I	0	VERTICAL	0.00	0.00	0.04
I	5000	VERTICAL	0.02	0.08	0.04
T	0	VERTICAL	0.00	0.00	0.06
T	5000	VERTICAL	0.03	0.03	0.10
L	0	VERTICAL	0.08	0.08	0.33
L	5000	VERTICAL	0.13	0.13	0.51
I	0	HORIZONTAL	0.13	0.13	0.19

- YAW CHANNEL CONTROL ONLY FOR NO TIP MASS



- YAW & PITCH CHANNEL CONTROL REQUIRED FOR TIP MASS



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UNDESIRABLE FLIGHT MODE STABILITY CONSIDERATIONS FOR REBOOST POINTING ATTITUDE CONTROL

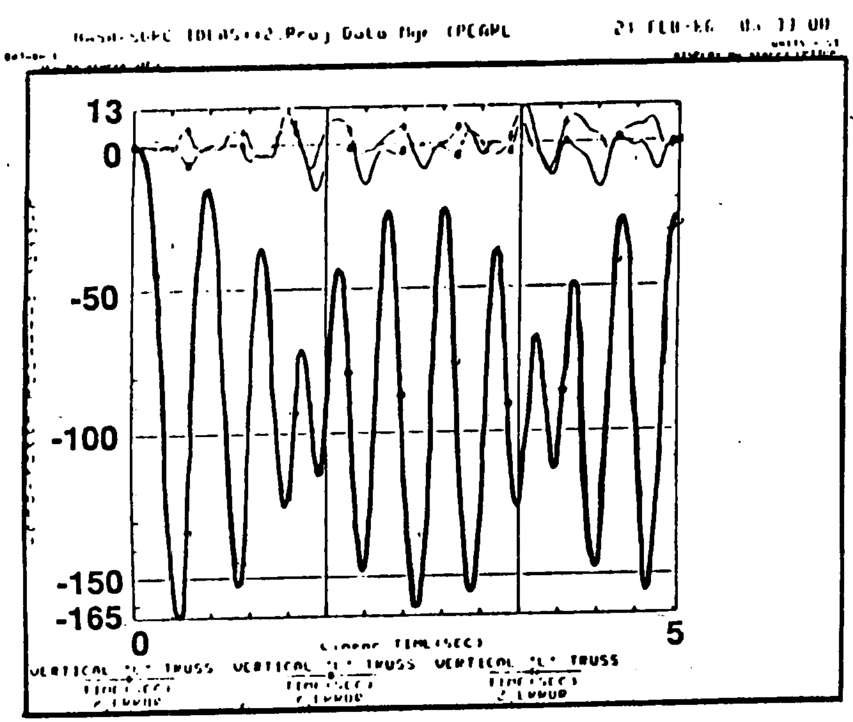
For the case "L" configuration undesirable yaw channel stability characteristics were seen over a 5 orbit observation period with yaw position errors varying up to 165 degrees.

For Horizontal Flight mode orientation considerations the vehicle position was observed to be unstable in all three axis. In all three initial configurations studied tumbling about all three axis was the observed characteristic.

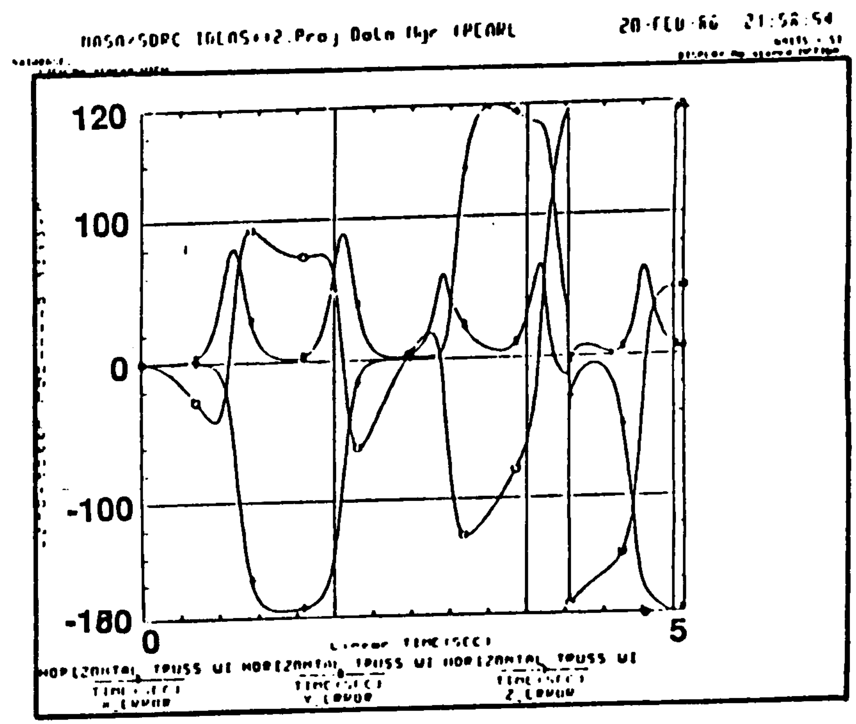
These instability characteristics would not be desirable and no further consideration should be given to "L" configuration or the horizontal flight mode for passive stabilization.

UNDESIRABLE FLIGHT MODE STABILITY CONSIDERATIONS FOR REBOOST POINTING ATTITUDE CONTROL

- "L" CONFIGURATION DEMONSTRATES EXCESSIVE YAW CHANNEL RESPONSE
- HORIZONTAL FLIGHT MODE SHOWS UNSTABLE CHARACTERISTICS IN ALL 3 AXES



Attitude error for "L" vertical truss with no tip mass.



Attitude error for "I" horizontal truss with no tip mass.

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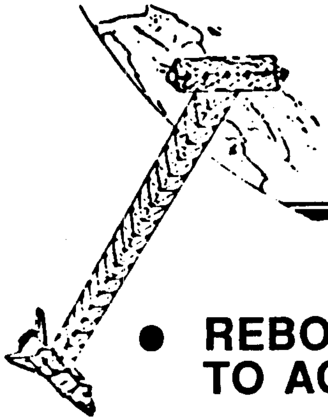
FREE FLIGHT MODE CONSIDERATIONS

Results of the initial configuration investigations show that reboost considerations with active pointing control will be a requirement if a free flight orbit lifetime is to be achieved for a mission launch in the 1989 time period. Orbital altitudes that must be considered would require either a manifesting on a direct ascent Shuttle mission to achieve altitude distances greater than standard 150 nautical mile Shuttle sortie flights, or an initial orbital altitude propulsive adjustment will be required immediately if deployed at this lower sortie altitude. The 270 nautical mile minimum altitude is recommended with reboost limit no lower than 220 nautical miles. This would require the consideration of about 2000 to 2700 pounds of propellant that must be considered to maintain orbit life for 3 years.

If EVA assembly verification timelines permit removal of tip mass it should be done because the added weight under consideration does not improve the flight ballistic coefficient and adds to control and stability resource requirements.

The "L" configuration should be eliminated from further consideration and the vertical flight mode (LV/LH) is recommended for further free flight considerations.



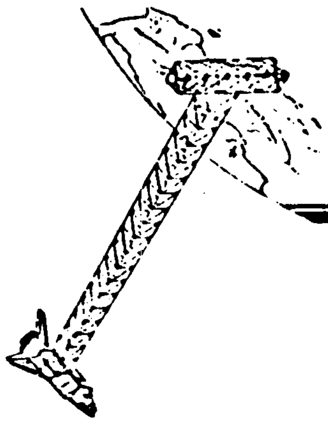
FREE FLIGHT MODE CONSIDERATIONS

- REBOOST WITH POINTING CONTROL WILL BE REQUIRED TO ACHIEVE A 3-YEAR ORBIT LIFE, FOR A 1989 LAUNCH
  - FOR INITIAL FREE FLIGHT DEPLOYMENT DIRECT ASCENT SHUTTLE FLIGHT MANIFESTING OR INITIAL ORBITAL ALTITUDE PROPULSIVE ADJUSTMENT IS REQUIRED
  - 270 NAUTICAL MILE MINIMUM INITIAL ALTITUDE IS REECOMMENDED WITH REBOOST NO LOWER THAN FROM 220 NMI
- REBOOST PROPELLANT REQUIREMENT AT Isp = 230 SEC IS 300 TO 400 KG/YR FOR TRUSS ONLY CONFIGURATIONS
- ANY TIP MASS WHICH WOULD CAUSE A CG/CP OFFSET SHOULD BE REMOVED OR RELOCATED TO CG PRIOR TO RELEASE IN ORDER TO REDUCE FLIGHT MODE ATTITUDE CONTROL REQUIREMENTS
- "L" CONFIGURATIONS SHOULD NOT BE LEFT IN ORBIT DUE TO STABILITY CONSIDERATIONS
- INITIAL ATTITUDE ORIENTATION SHOULD BE VERTICAL, SINCE THIS IS THE GRAVITY-STABILIZED ORIENTATION FOR THE "I" AND "T" CONFIGURATIONS

"T" TRUSS WITH UTILITY TRAYS & S/C BUS ANALYSIS

Based on initial investigations the "T" truss was baselined by the study team and described to all team members by Boeing Company letter in April of 1986 which specified the physical characteristics for the truss structure, desired tip mass, utility trays and budget weight for a spacecraft bus. Further analysis was undertaken to characterize the orbit decay and reboost characteristics of the baselined configuration. Deterministic studies of gravity gradient stabilized flight attitude and body axis stability characteristics were performed.

At this point it was also deemed necessary to synthesize a spacecraft bus design for sizing and costing purposes to assess the impacts to maintain the 3 year orbital lifetime mission goal.

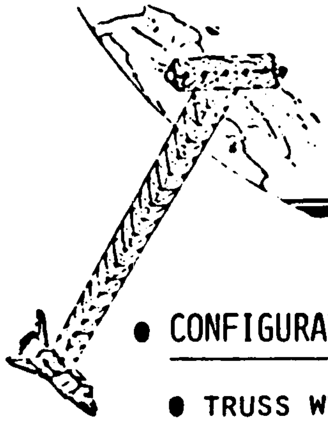


"T" TRUSS WITH UTILITY TRAYS & S/C BUS ANALYSIS

- "T" TRUSS CONFIGURATION AS SPECIFIED BY BAC LETTER 2-1673-DHB-049, DATED APRIL 22, 1986 (UPDATE TO 4/14/86 LETTER).
  - PHYSICAL CHARACTERISTICS SPECIFIED FOR TRUSS, TIP MASS, UTILITY TRAYS, AND SPACECRAFT BUS
  - THREE FLIGHT MODE ORIENTATION ANALYSIS REQUESTED
    - DETERMINE ORBIT DECAY AND REBOOST CHARACTERISTICS
    - DETERMINE GRAVITY GRADIENT STABILIZED ATTITUDE AND STABILITY CHARACTERISTICS
- DETERMINE FREE FLYER SPACECRAFT BUS ROM COSTS.

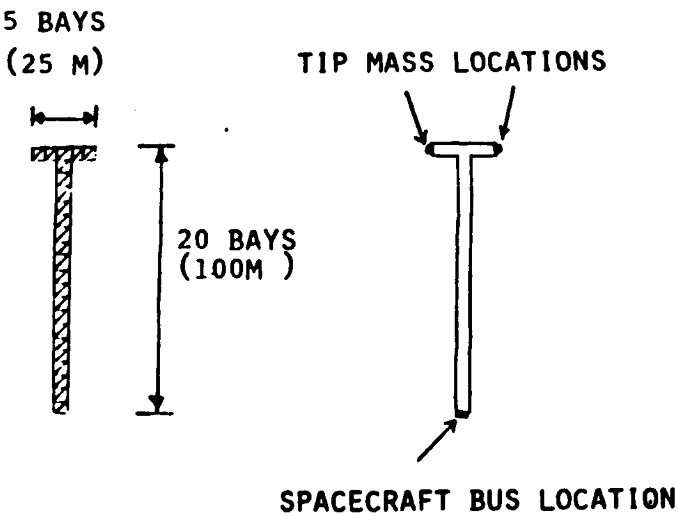
"T" TRUSS CONFIGURATION CHARACTERISTICS

The baseline configuration geometry and weight budgets are shown. Two options for utility tray locations are shown for a 100 meter full length run and a double run of 50 meters.

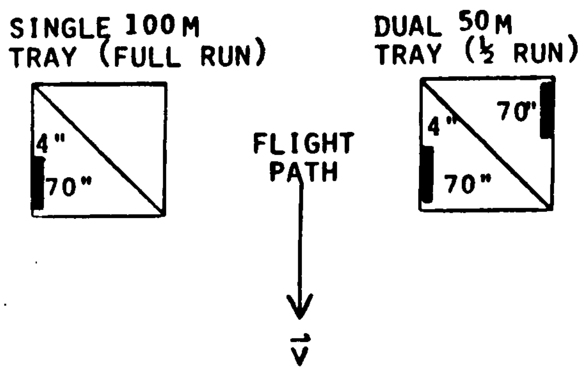


"T" TRUSS CONFIGURATION CHARACTERISTICS

- CONFIGURATION GEOMETRY
  - TRUSS WT = 3600 LBS
  - TIP MASS = 1000 LBS EACH
  - SPACECRAFT BUS = 3000 LB



- UTILITY TRAY LOCATION GEOMETRY (TOP VIEW)
  - TRAY SIZE = 70″ WIDE
    (DUAL 30″+40″ TRAYS)
    = 4″ THICK
  - TRAY WEIGHT = 6300 LBS

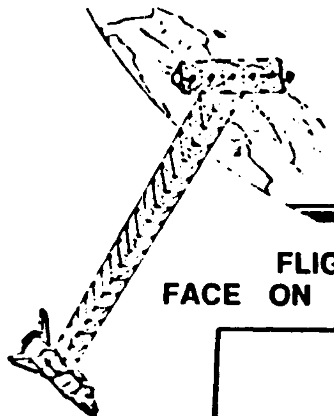


FLIGHT MODE ORIENTATION ANALYSIS

Three flight mode orientations were investigated. The "face on" orientation and the "edge on" orientation were derived from assembly build-up options under consideration which could leave the final configuration with the utility trays and upper cross truss of the "T" in any of the possible configuration options shown on the following pages.

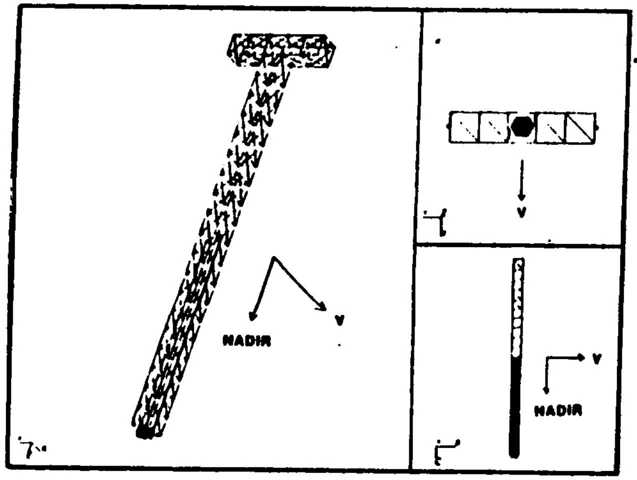
Although the "end on" or horizontal flight mode orientation has been shown to exhibit unstable characteristics, it was investigated further to characterize its control requirement for a reboost manuever. It is initially judged to be more oriented for thrust vector control through the configurations center of gravity for a spacecraft utility bus reboost engine located at the position shown on the previous page.

The following pages will show detail drawings of truss and tray geometries for the 100 meter and 50 meter utility tray options for all three flight mode orientations investigated.

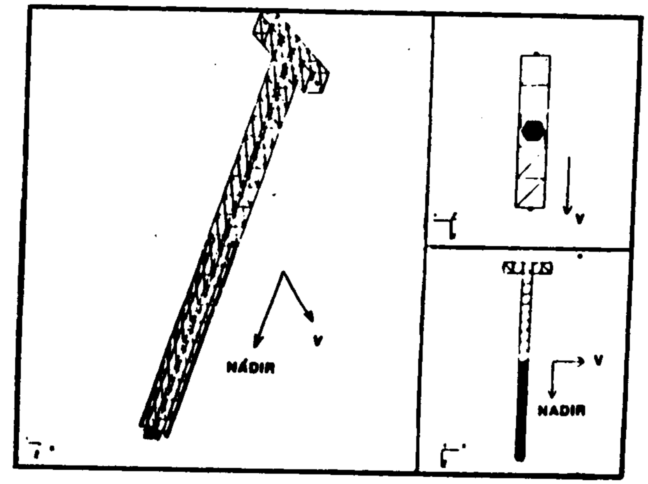


FLIGHT MODE ORIENTATION ANALYSIS

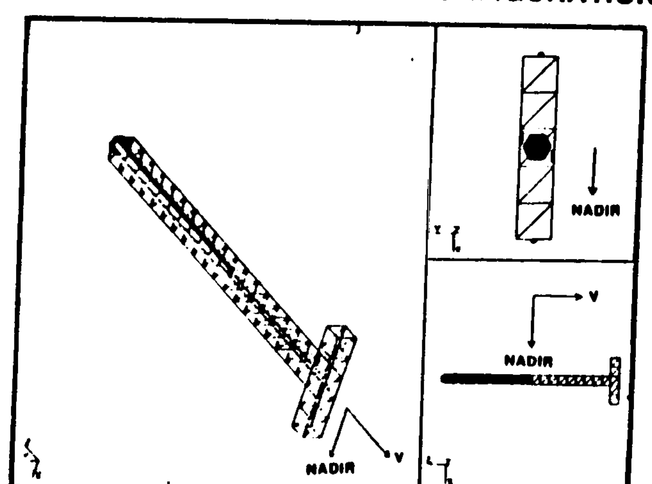
FLIGHT MODE ORIENTATION #1
FACE ON 50-METER TRAY CONFIGURATION



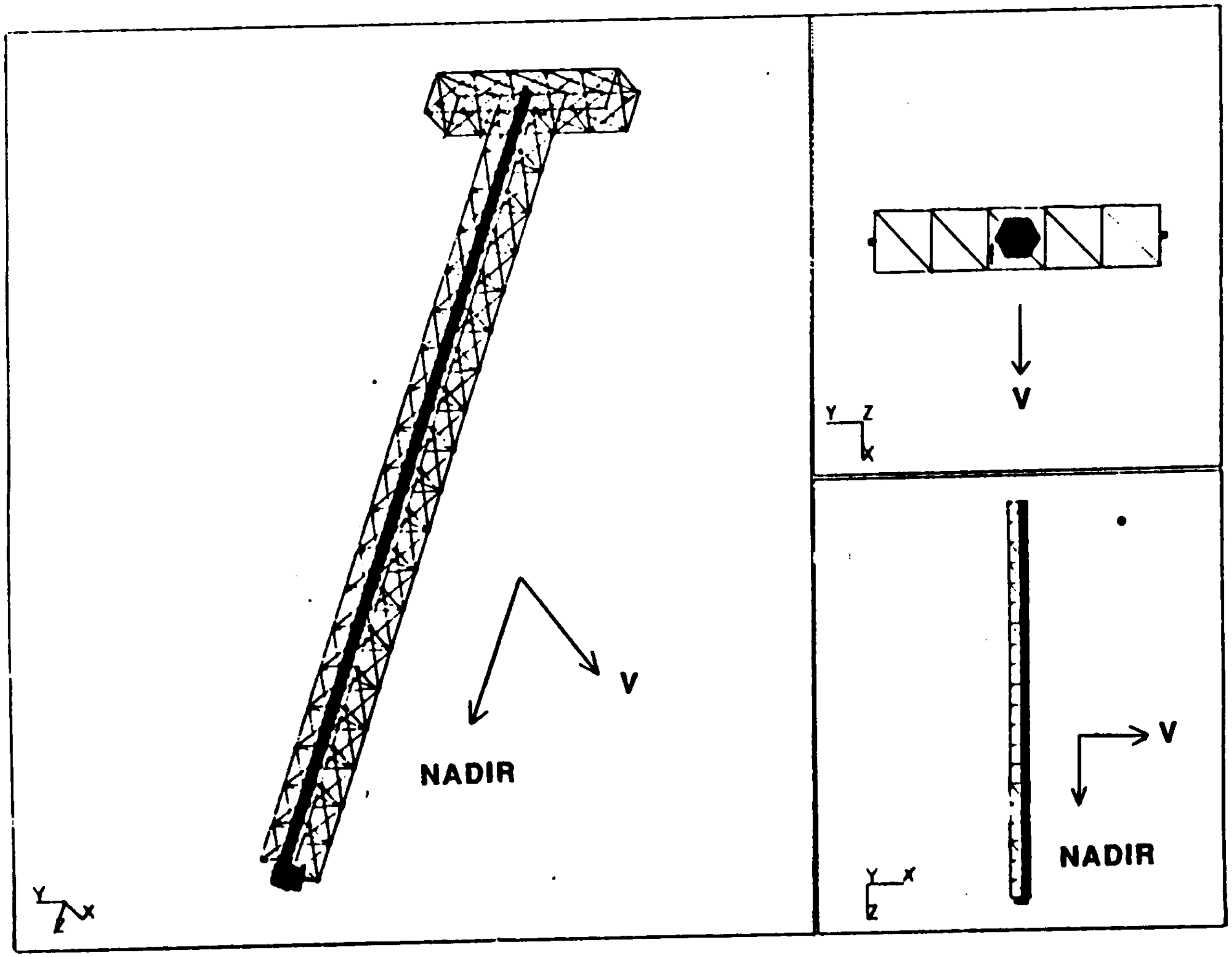
FLIGHT MODE ORIENTATION #2
EDGE ON 50-METER TRAY CONFIGURATION



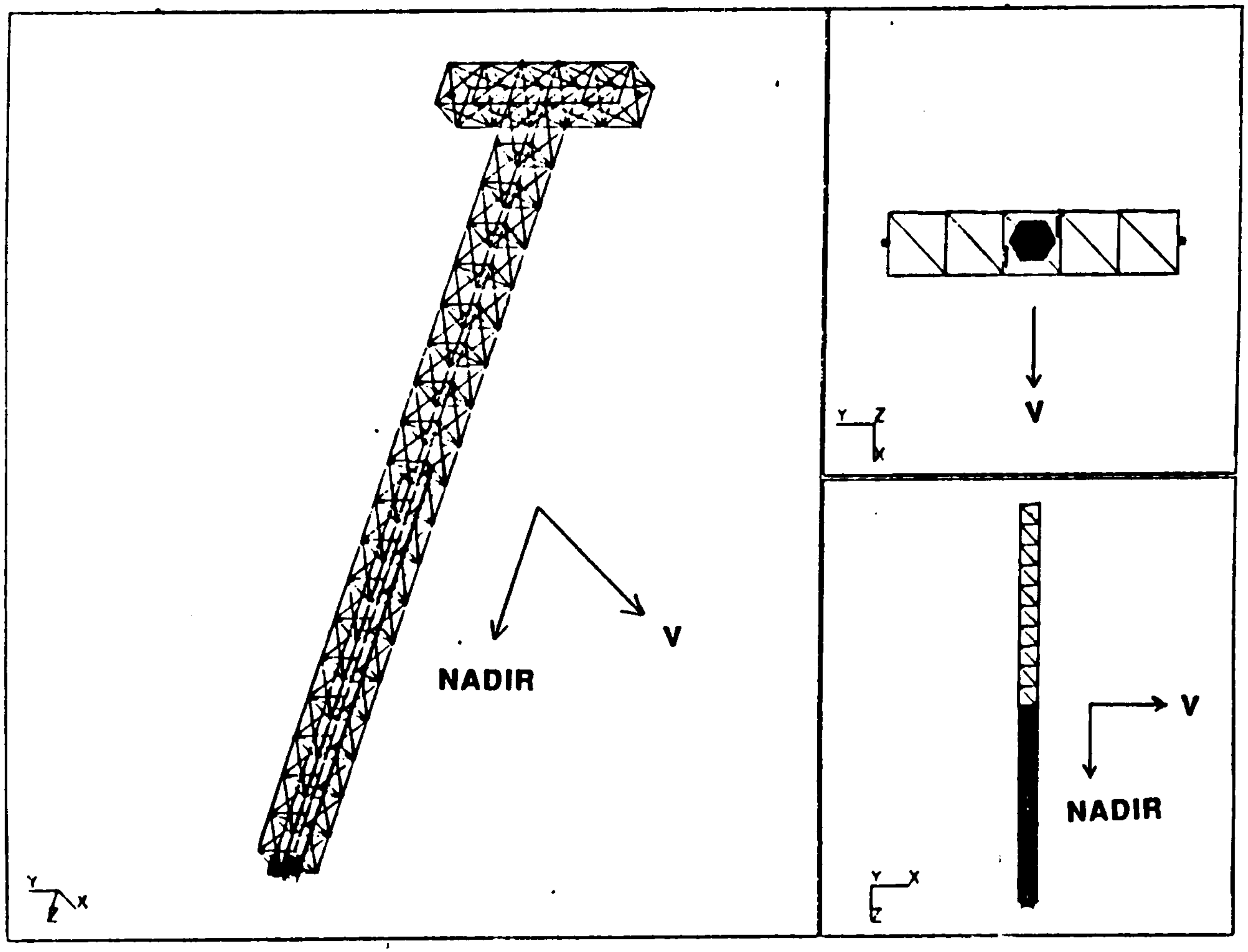
FLIGHT MODE ORIENTATION #3
END ON 50-METER TRAY CONFIGURATION



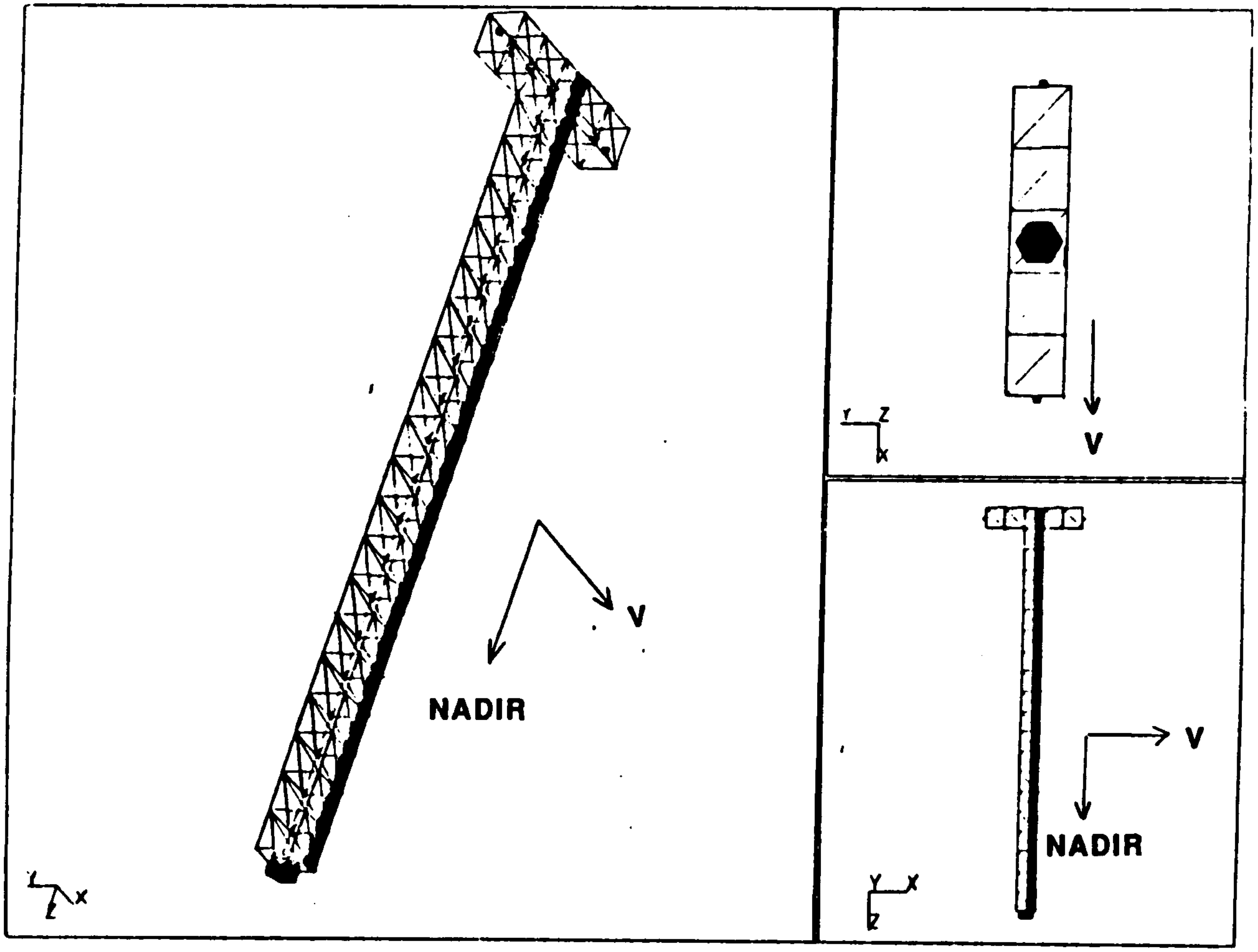
FLIGHT MODE ORIENTATION #1
FACE ON 100-METER TRAY CONFIGURATION



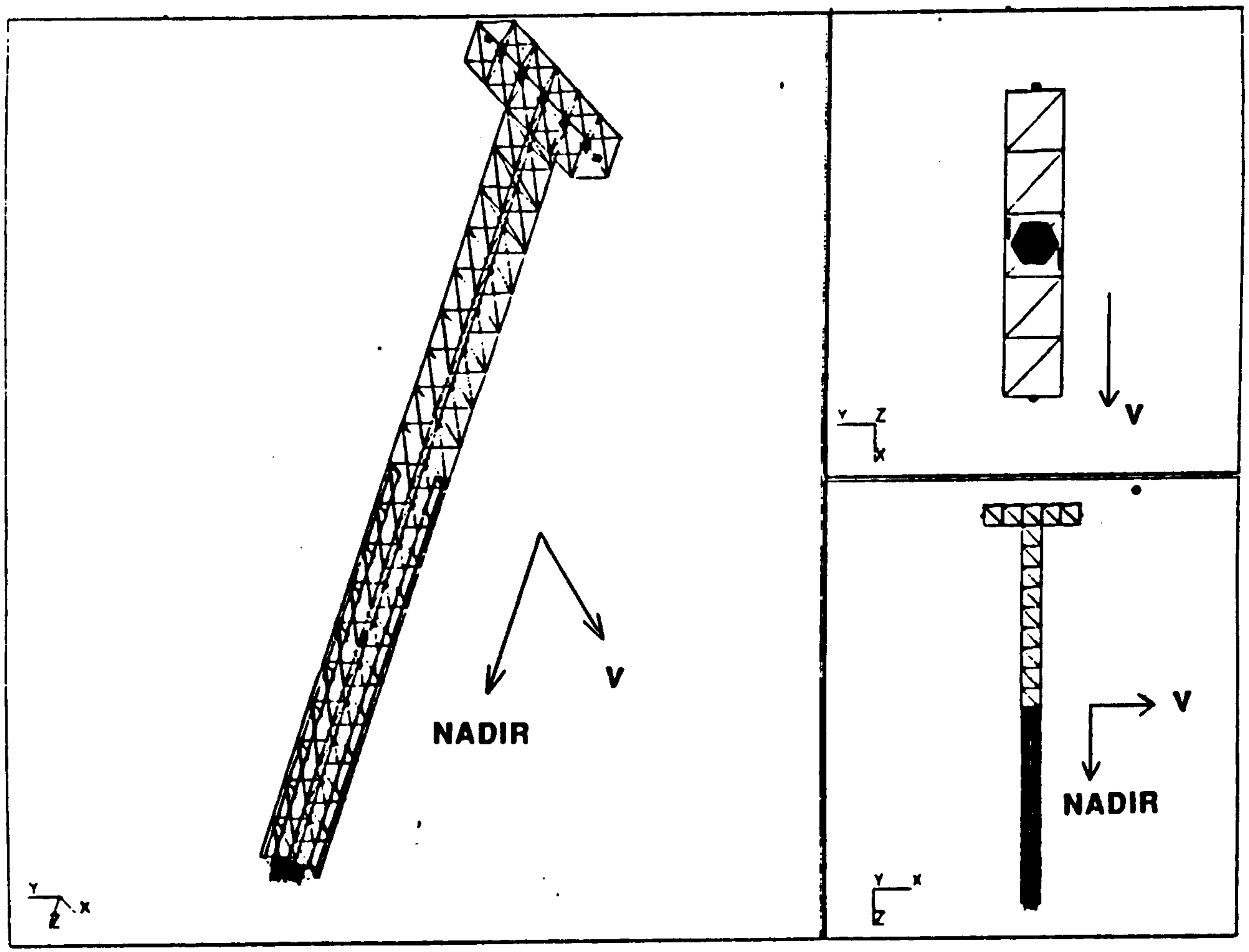
FLIGHT MODE ORIENTATION #1
FACE ON 50-METER TRAY CONFIGURATION



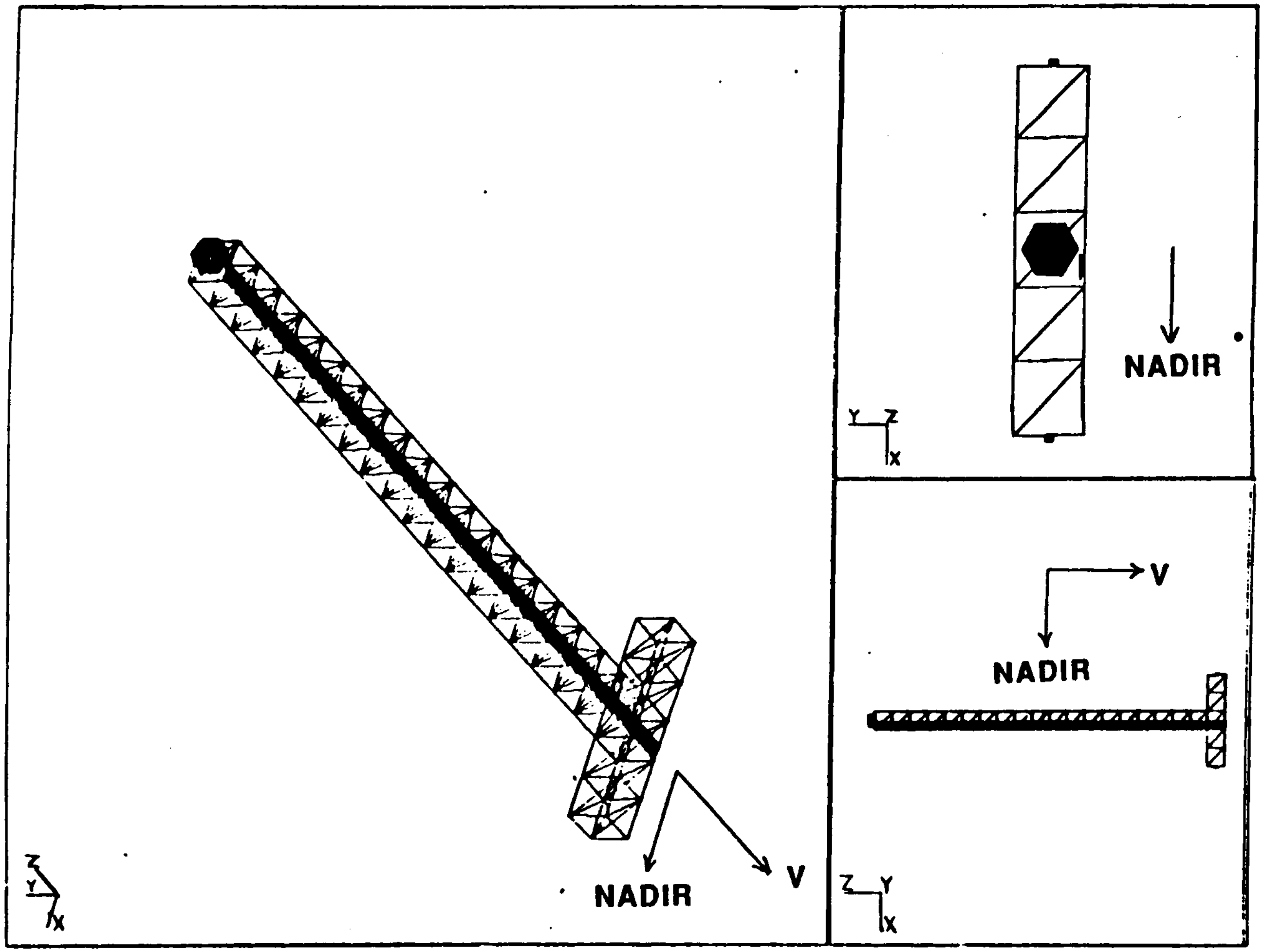
FLIGHT MODE ORIENTATION #2
EDGE ON 100-METER TRAY CONFIGURATION



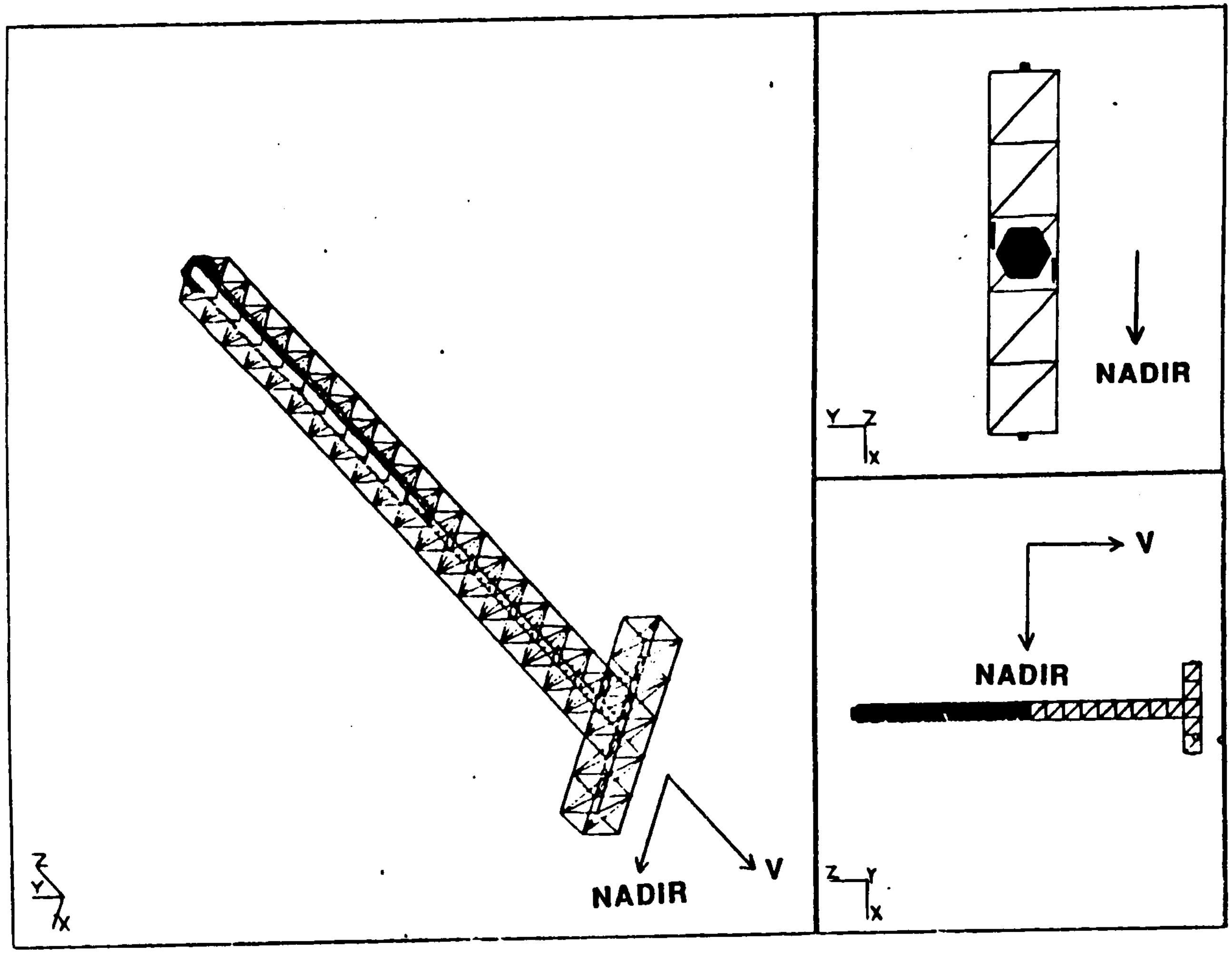
FLIGHT MODE ORIENTATION #2
EDGE ON 50-METER TRAY CONFIGURATION



FLIGHT MODE ORIENTATION #3
END ON 100-METER TRAY CONFIGURATION



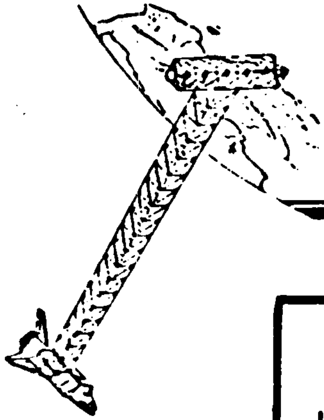
FLIGHT MODE ORIENTATION #3
END ON 50-METER TRAY CONFIGURATION



PHYSICAL CHARACTERISTICS

The physical characteristics of the baseline configuration options are summarized here for comparison. The larger weights and aerodynamic drag areas shown for these options over those derived for the initial configuration geometries investigated are due to the addition and locations of the utility trays. The 50 meter configurations display the better principal inertia axis to body axis alignment with zero Ixz and Iyz inertia cross products which would forecast good gravity gradient stability characteristics.

Physical characteristics for the SAVE configuration options were determined assuming that no truss elements block other truss elements. This is a conservative but realistic assumption from an orbit decay analysis point of view since a small misalignment of the truss with the velocity vector would give rise to this situation. Furthermore, drag areas were computed for SAVE flying at the torque equilibrium attitude for all six configurations. Products of inertia Ixz and Iyz are identically zero for the dual 50 m tray configurations due to the symmetry in the xz and yz planes.

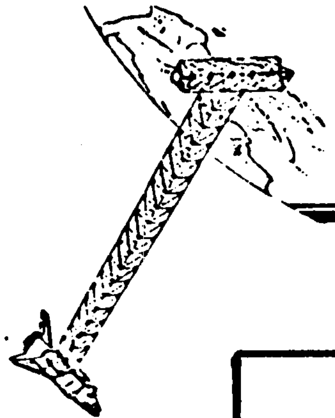


PHYSICAL CHARACTERISTICS

	FACE ON 100 METER UTILITY TRAYS	FACE ON 50 METER UTILITY TRAYS	EDGE ON 100 METER UTILITY TRAYS	EDGE ON 50 METER UTILITY TRAYS	END ON 100 METER UTILITY TRAYS	END ON 50 METER UTILITY TRAYS
MASS (kg)	6650	6650	6650	6650	6650	6650
DRAG AREA (M^2)	111	120	111	111	104	104
INERTIA (kg m^2)						
IXX	9.73 E6	8.68 E6	9.57 E6	8.51 E6	9.57 E6	8.51 E6
IYY	9.56 E6	8.50 E6	9.73 E6	8.66 E6	9.73 E6	8.66 E6
IZZ	1.89 E5	1.99 E5	1.89 E5	1.99 E5	1.89 E5	1.99 E5
IXY	5.09 E3	8.91 E3	-5.09 E3	-8.91 E3	-5.09 E3	-8.91 E3
IXZ	-7.49 E3	0	-7.49 E3	0	-7.49 E3	0
IYZ	-1.50 E4	0	1.50 E4	0	1.50 E4	0

ORBIT DECAY ANALYSIS

An orbit decay analysis was undertaken for a 2σ atmosphere and April 1, 1989, initial operation (solar flux = 126.8 10^{-22} W/m^2 /Hz, geomagnetic index = 16.3). With no reboost, all configurations were seen to decay from 270 NM to 220 NM in a year, and from 250 NM to 220 NM in just over half a year. The "end on" configurations have a slightly longer decay time and hence require less orbit keep propellant than the "face on" and "edge on" configurations. A calculated propellent reboost weight budget fror these baseline configuration options is approximately 1000 pounds for a 3 year mission lifetime goal.



ORBIT DECAY ANALYSIS

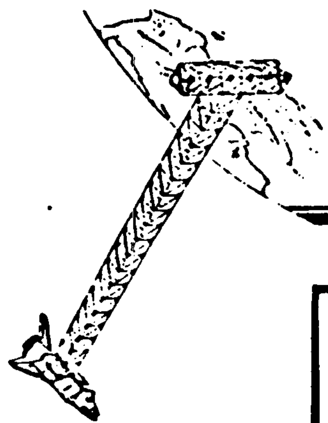
	BALLISTIC COEFFICIENT (kg/m**2)	DECAY TIME (DAYS)		ORBIT KEEP PROPELLANT REQ'T @ I_{SP} = 230 (KG / YR)
		270 — 220NM	250 — 220 NM	
FACE ON 100 METER UTILITY TRAYS	26	353	195	137
FACE ON 50 METER UTILITY TRAYS	24	334	184	152
EDGE ON 100 METER UTILITY TRAYS	26	353	195	137
EDGE ON 50 METER UTILITY TRAYS	26	353	195	137
END ON 100 METER UTILITY TRAYS	28	370	198	127
END ON 50 METER UTILITY TRAYS	28	370	198	125

ASSUMPTION: 2σ ATMOSPHERE, APRIL 1, 1989 INITIAL OPERATION

CONTROLLABILITY & STABILITY ANALYSIS

The stability and control analysis performed shows that only small angular momentum absorption devices on the order of 100 Newton meter second (approximately 80 ft. lb. sec) would be required to maintain body axis orientation in any attitude desired. The small torque equilibrium angles calculated, which align the body axis to minimize secular momentum build up, are extremely small and are the result of the close alignment of the principal inertia axis to the vehicle body axis. The uncontrolled attitude peak error rates also are very small (observed over a 5 orbit simulation period) indicating that periods of passive stabilization between reboost maneuvers could be considered.

Only the "edge on" configurations yielded acceptable stability characteristics for consideration for long-term passive stabilization as will be explained in the pages to follow.



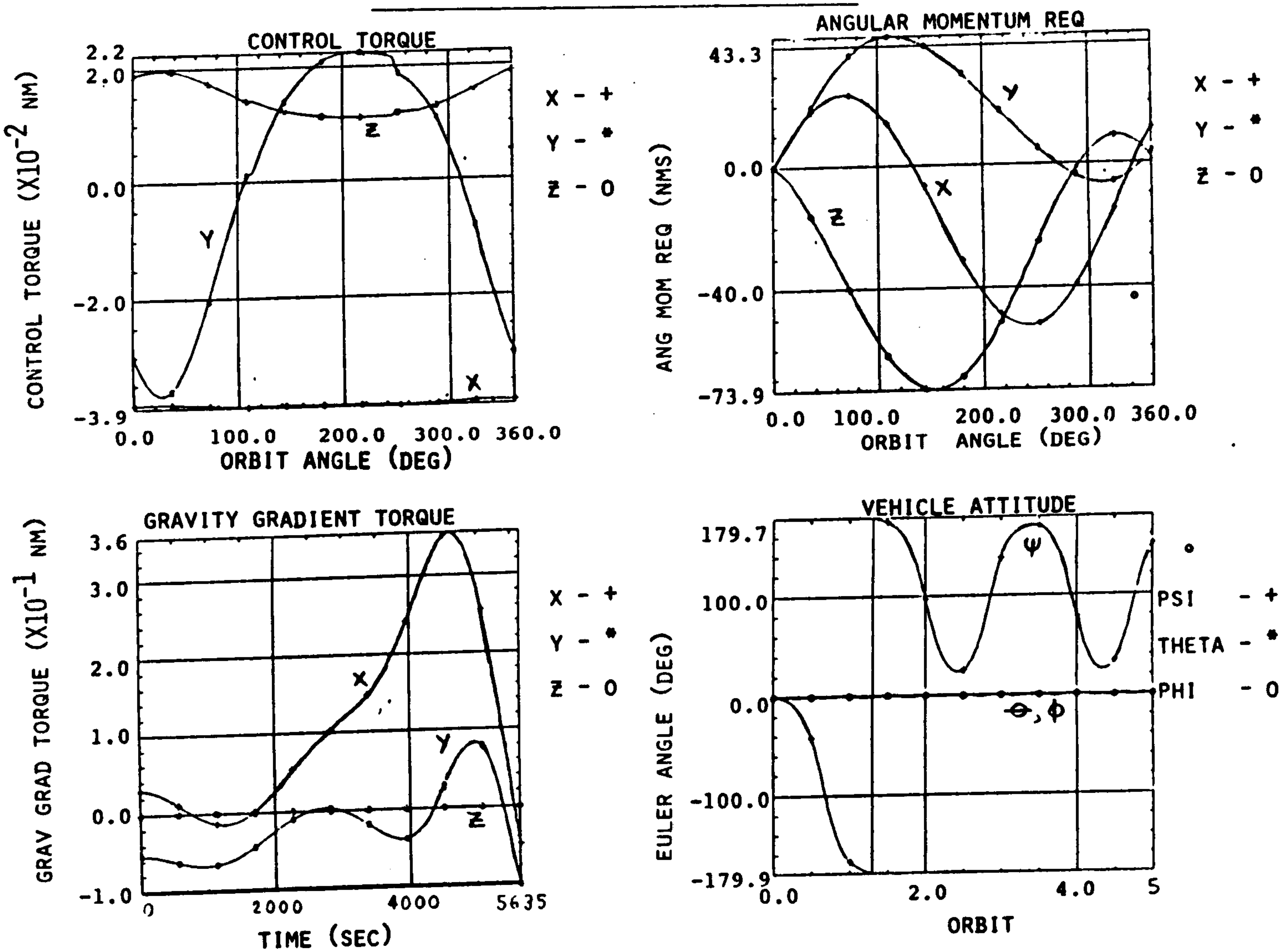
CONTROLLABILITY & STABILITY ANALYSIS

	TORQUE EQUILIBRIUM ANGLE			PEAK ANGULAR MOMENTUM REQ'T (NMS)	PEAK RATE (deg/sec)	STABILITY
	PSI (Z)	THETA (Y)	PHI (X)			
FACE ON 100 METER UTILITY TRAYS	0	0.13	-0.14	73.9	0.07	UNSTABLE
FACE ON 50 METER UTILITY TRAYS	1.63	0.24	0.01	104.2	0.07	UNSTABLE
EDGE ON 100 METER UTILITY TRAYS	0	0.13	0.13	63.1	0.06	STABLE
EDGE ON 50 METER UTILITY TRAYS	0	0.25	0	100.7	0.06	STABLE
END ON 100 METER UTILITY TRAYS	0	0.04	0.24	48	0.06	UNSTABLE
END ON 50 METER UTILITY TRAYS	0	0	-0.01	86.6	0.17	UNSTABLE

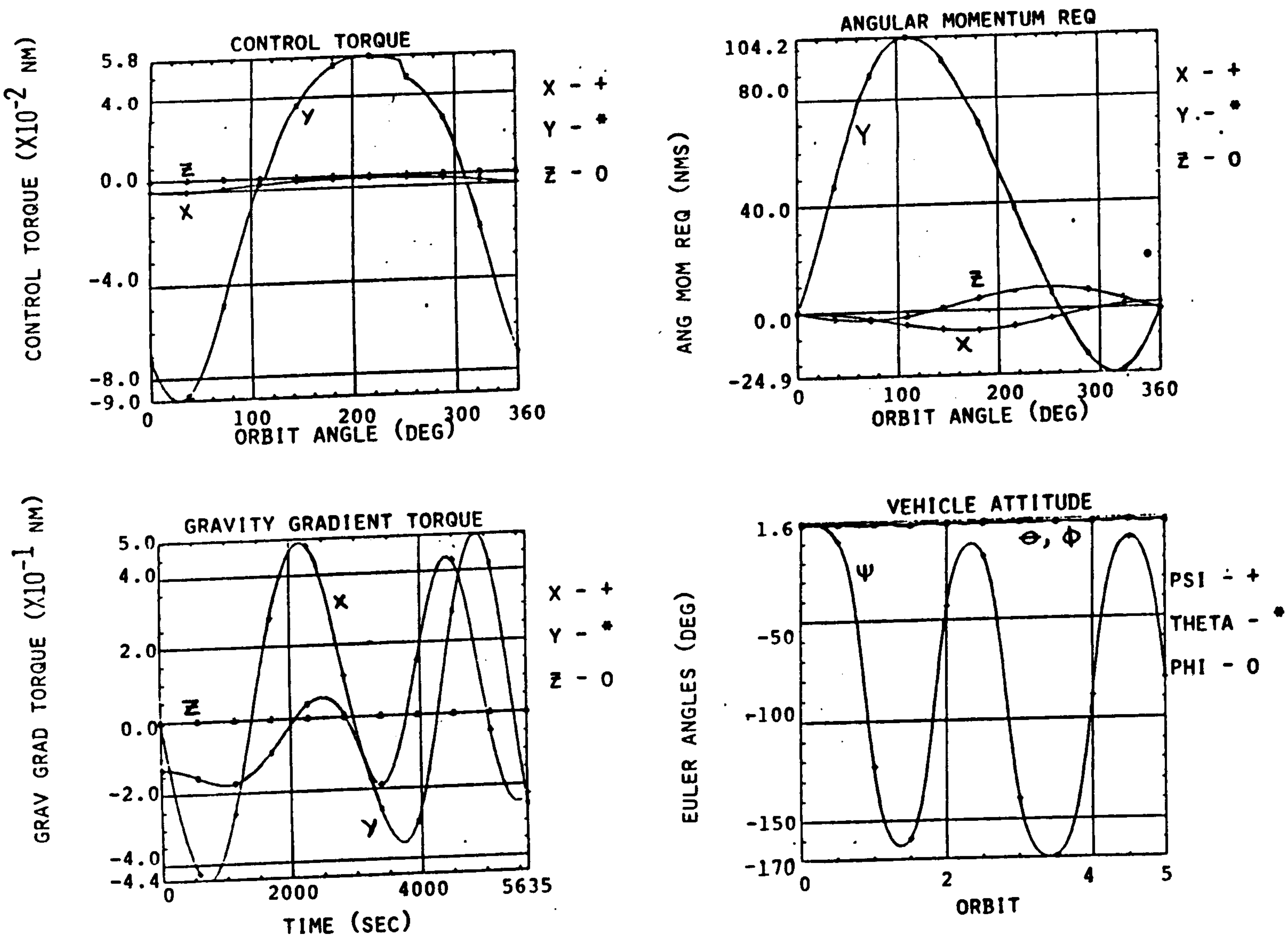
FACE ON WITH 100-METER UTILITY TRAYS

The following six figures show control torque and angular momentum required to maintain a fixed attitude over one orbit, gravity gradient torque of an uncontrolled free flying SAVE over one orbit, and vehicle attitude 3-2-1 Euler angles for an uncontrolled free flying SAVE over five orbits. All six configurations require relatively small control torques (0.08 NM maximum) to maintain a fixed attitude at the TEA. Gravity gradient torques on the free flying uncontrolled SAVE are relatively small (0.5 NM maximum) for the "face on" and "edge on" configurations; however, a large gravity gradient torque (15 NM) is exerted on the unstable "end on" configuration when flying with no control. Because the "face on" and "edge on" configurations are very sensitive in yaw, the dual 50 m utility tray configurations exhibit better stability characteristics in an uncontrolled free flight mode since they have higher Izz. The "edge on" 50 m tray configuration is the most stable in uncontrolled flight mode.

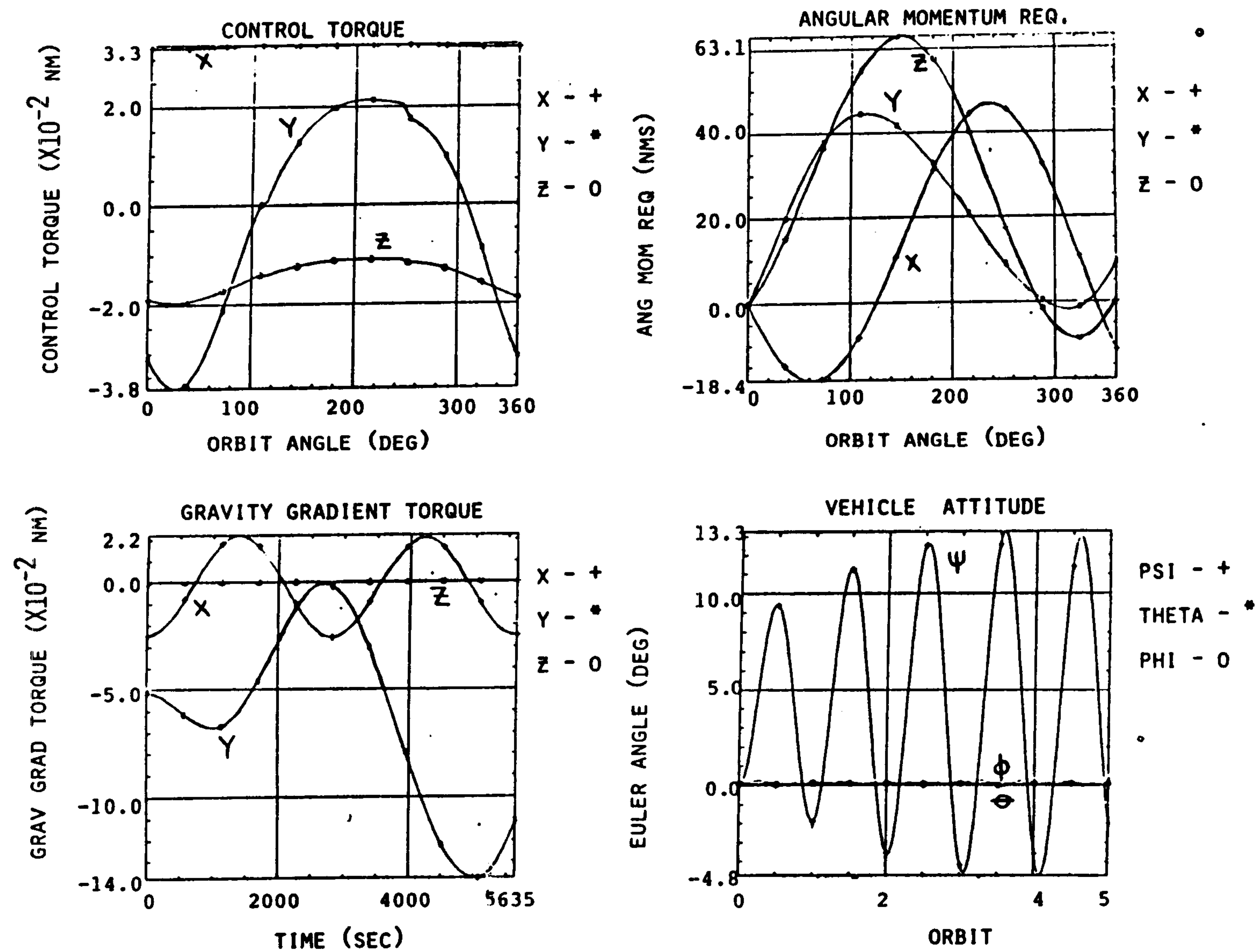
FACE ON WITH 100-METER UTILITY TRAYS



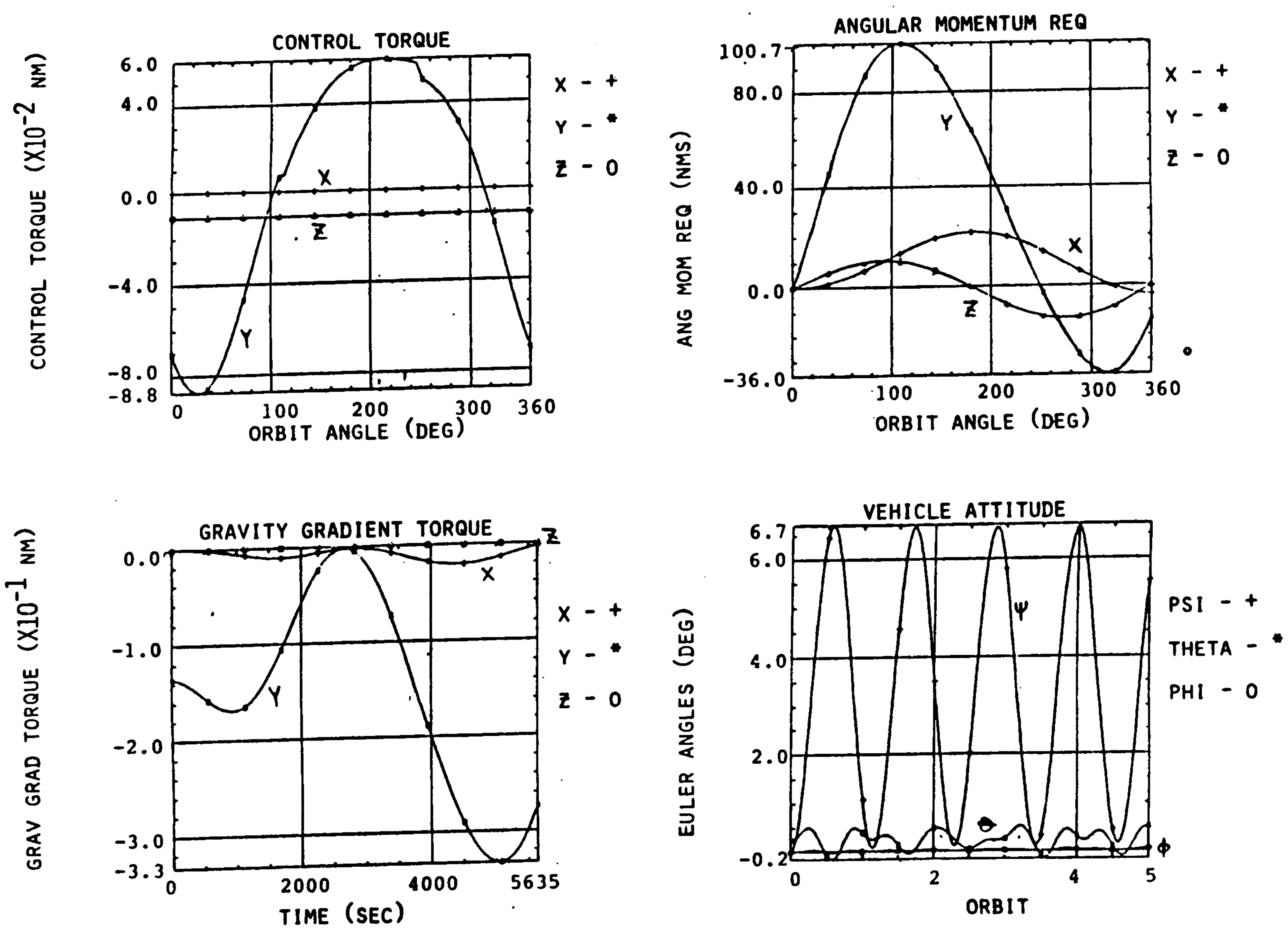
FACE ON WITH 50-METER UTILITY TRAYS



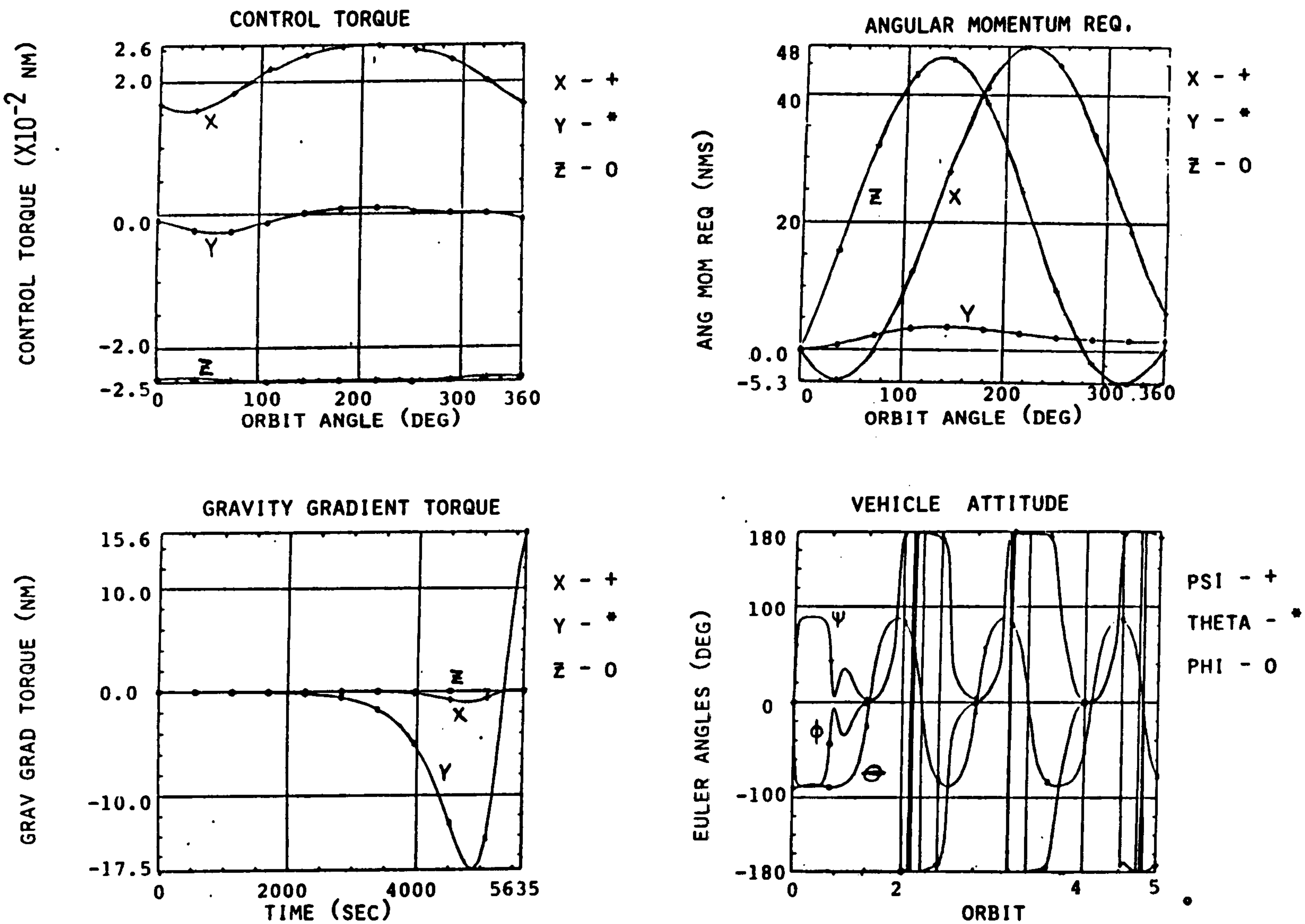
EDGE ON WITH 100-METER UTILITY TRAYS



EDGE ON WITH 50-METER UTILITY TRAYS



END ON WITH 100-METER UTILITY TRAYS



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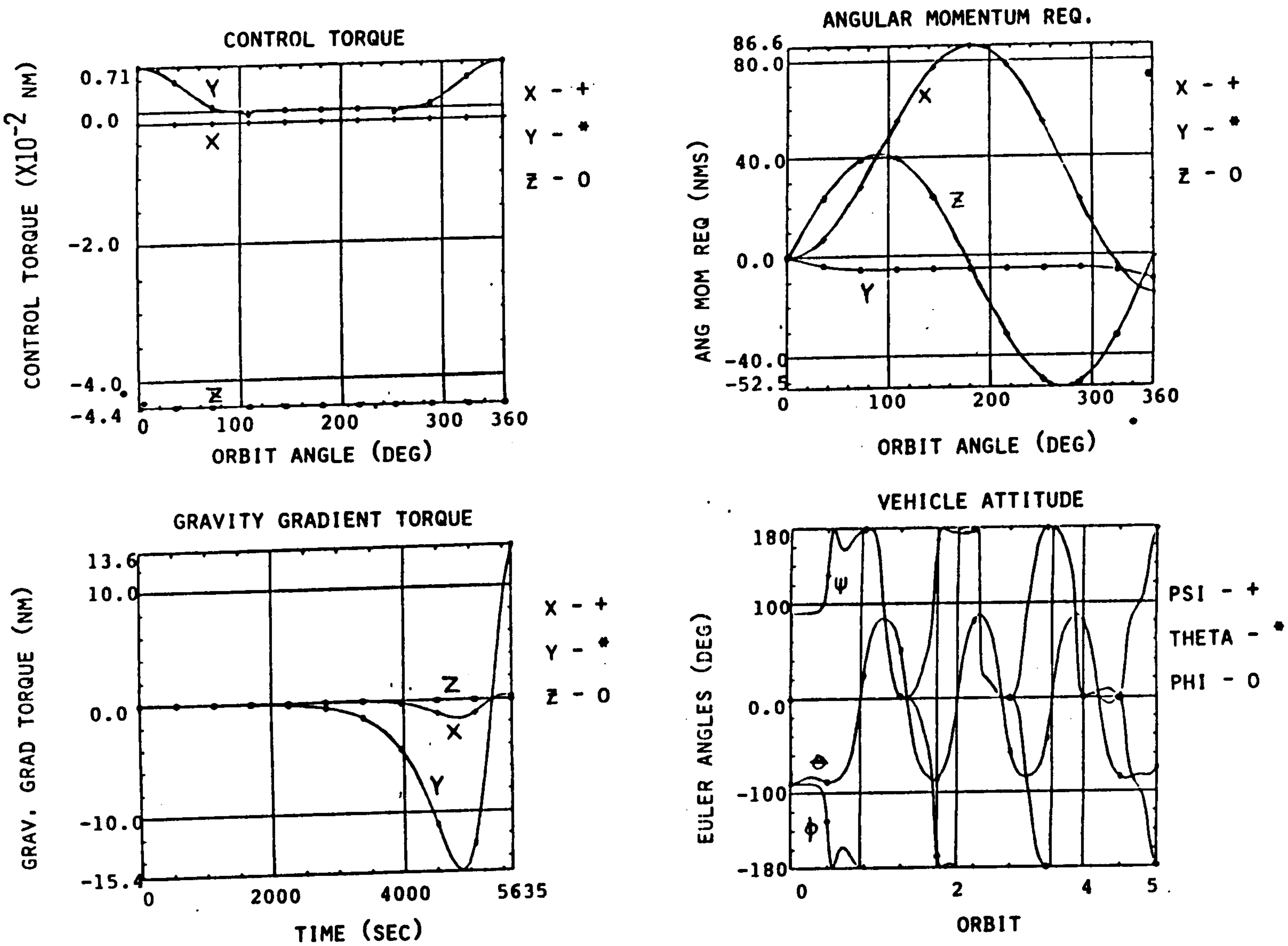
END ON WITH 50-METER UTILITY TRAYS



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EQUILIBRIUM STABILITY

Roll-yaw stability requires that Iy be either the minimum or maximum moment of inertia, and

$$1 + 3\left(\frac{Iy - Iz}{Ix}\right) + \left(\frac{Iy - Ix}{Iz}\right)\left(\frac{Iy - Iz}{Ix}\right) > 4\sqrt{\left(\frac{Iy - Ix}{Iz}\right)\left(\frac{Iy - Iz}{Ix}\right)}$$

The "edge on" configuration with the centered trays satisfies these stability criteria and hence exhibits very stable free flight mode characteristics. The "face on" configuration with centered trays does not satisfy the roll-yaw stability criteria and will in fact try to orient itself into an "edge on" position if left in an uncontrolled free flight mode. The same general trends were observed for the "face on" and "edge on" configurations with uncentered utility trays.

The equilibrium stability characteristics of the "face on" and "edge on" configurations were further investigated for zero cross-product moments of inertia by centering the 100 m utility trays in the truss. If the principal axis are misaligned from the Local Vehicle/Local Horizontal (LVLH) by small rotations Ψx (roll), Ψy (pitch), and Ψz (yaw), then Eulers equations may be written to first order

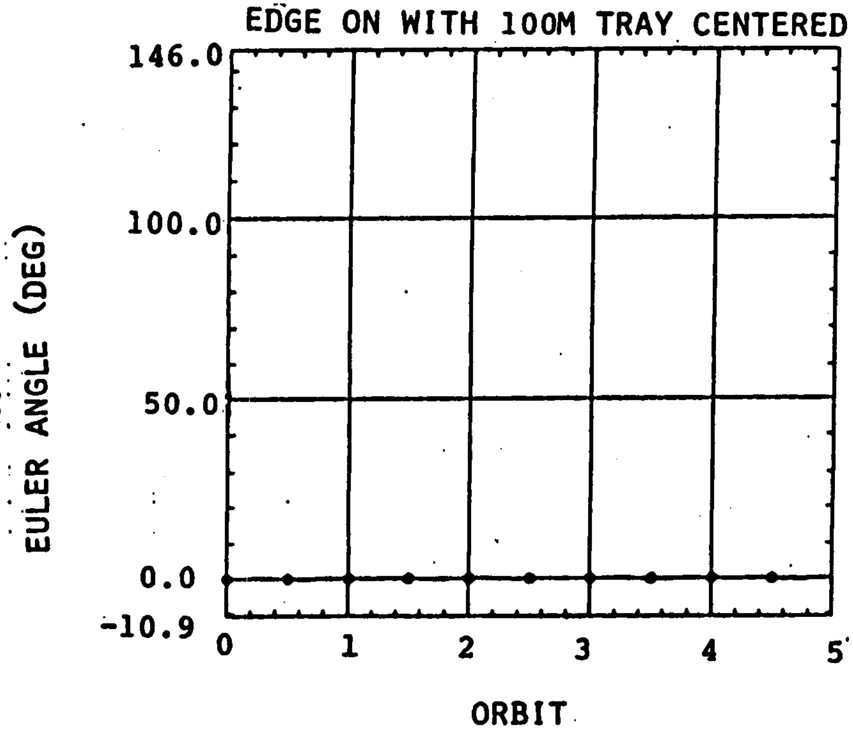
$$I_x\,(\ddot{\Psi}_x - \omega_0\dot{\Psi}_z) + (I_z - I_y)\,(-\omega_0\dot{\Psi}_z - \omega_0^2\Psi_x) = 3\omega_0^2\,(I_z - I_y)\,\Psi_x$$

$$I_y\ddot{\Psi}_y = -3\omega_0^2\,(I_x - I_z)\,\Psi_y$$

$$I_z\,(-\ddot{\Psi}_z - \omega_0\dot{\Psi}_x) + (I_y - I_x)\,(\omega_0\dot{\Psi}_x - \omega_0^2\Psi_z) = 0$$

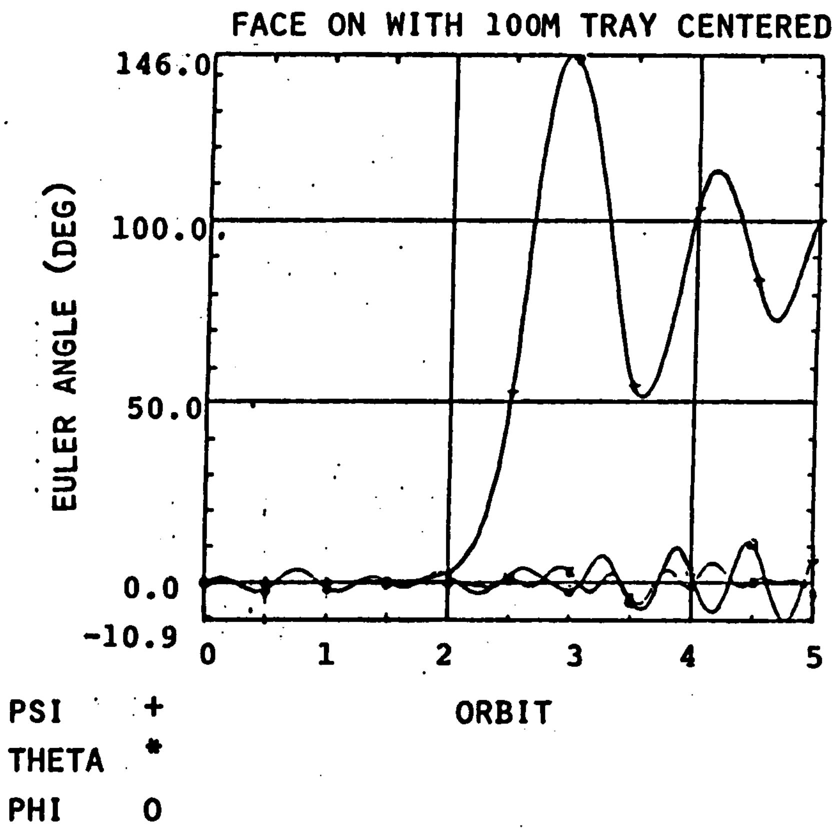
where ω_0 is the orbital rate. An inspection of these equations reveals that gravity gradient torques are exerted in roll and pitch axis only, and that the roll and yaw equations are coupled. For pitch stability, $Ix > Iz$.

EQUILIBRIUM STABILITY



$I_{PITCH} > I_{ROLL} > I_{YAW}$

STABLE EQUILIBRIUM



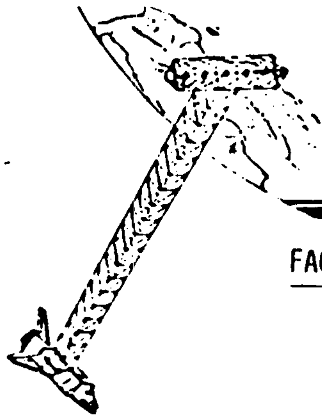
$I_{ROLL} > I_{PITCH} > I_{YAW}$

UNSTABLE EQUILIBRIUM

STABILITY ANALYSIS SUMMARY

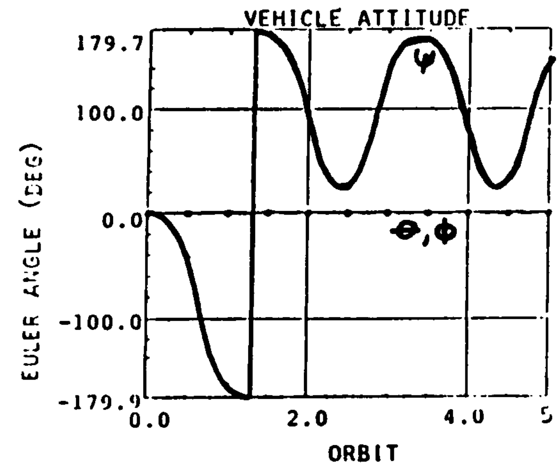
A summary of the stability analysis of the SAVE baseline configuration options are shown which depicts the large uncontrolled yaw angle attitude error position excursions of -180 degrees for the "face on" with 100 meter tray runs and -170 degree excursion of "face on" with 50 meter drag runs. Both "face on" configurations tend to want to align themselves to the "edge on" position over a period of several orbits if left in an uncontrolled model.

The more favorable uncontrolled attitude error-position of the "edge on" configuration options are also shown. The "edge on" option with fifty meter tray runs is the best candidate for passive stabilization since it displays a peak attitude error position of only 7 degrees.

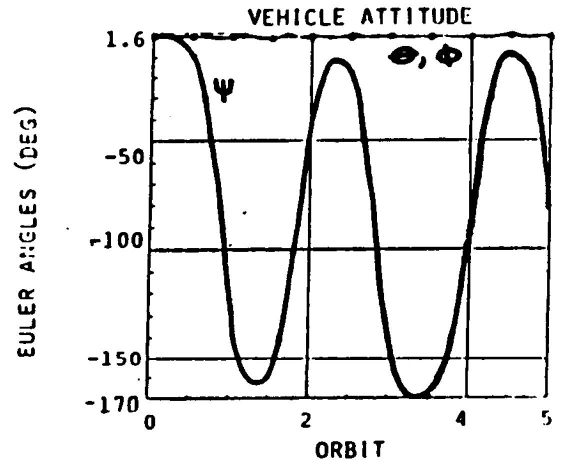


STABILITY ANALYSIS SUMMARY

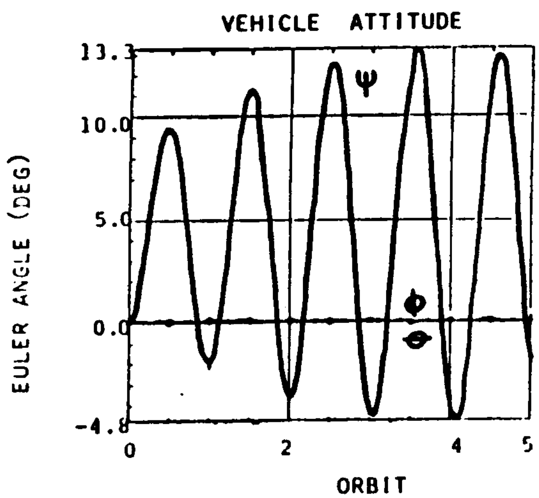
FACE ON WITH 100-METER UTILITY TRAYS



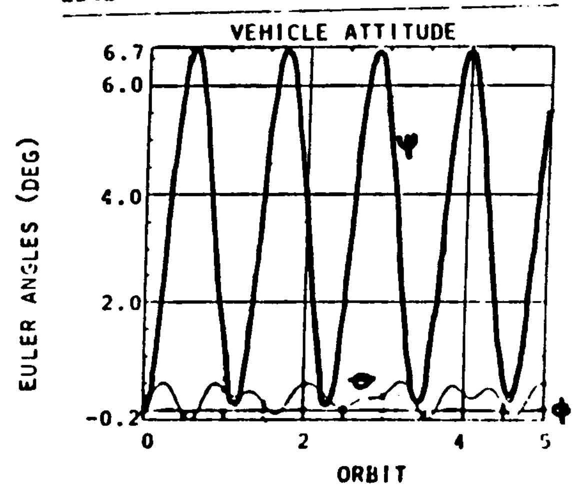
FACE ON WITH 50-METER UTILITY TRAYS



EDGE ON WITH 100-METER UTILITY TRAYS

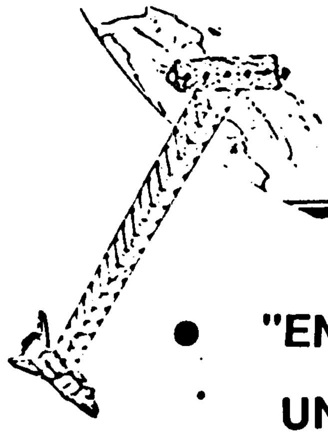


EDGE ON WITH 50-METER UTILITY TRAYS



END ON FLIGHT MODE ORIENTATION

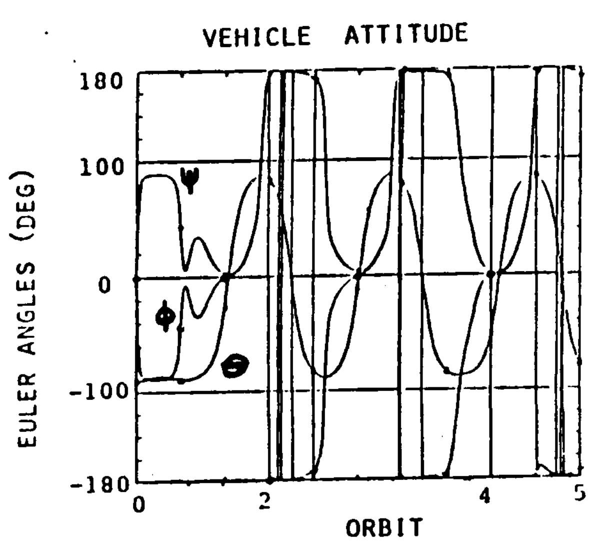
Analysis again shows that the end on configuration options are unstable and exhibit tumbling motions about all three axis and should not be left in an uncontrolled mode in this initial orientation position.



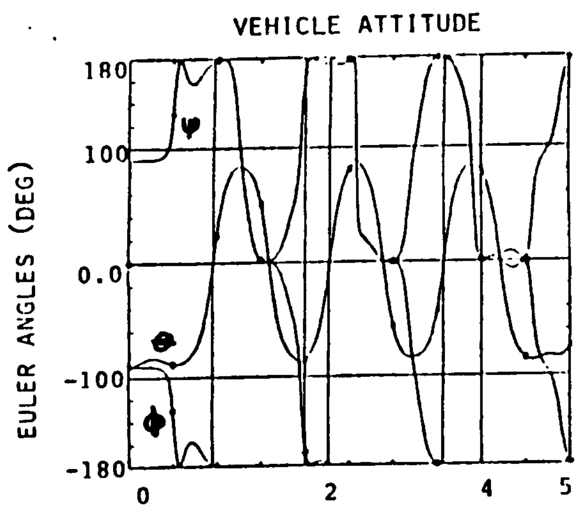
END ON FLIGHT MODE ORIENTATION

- "END ON" FLIGHT MODE ORIENTATION EXHIBITS UNSTABLE FREE FLIGHT MODE CHARACTERISTICS

END ON WITH 100-METER UTILITY TRAYS

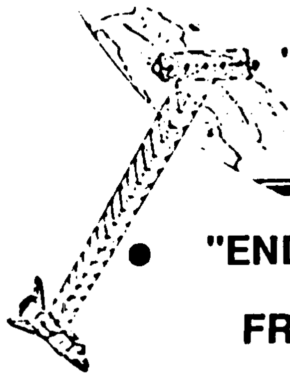


END ON WITH 50-METER UTILITY TRAYS



"T" TRUSS CONFIGURATION MODE ORIENTATION ANALYSIS SUMMARY

A summary of the investigation of the baseline "T" SAVE configuration options is presented.



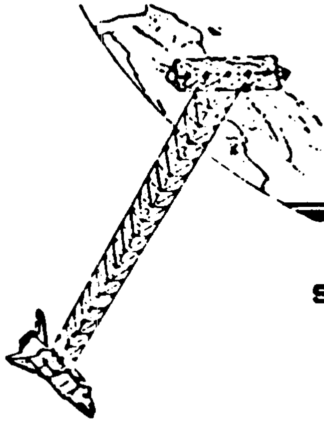
'T' TRUSS CONFIGURATION MODE ORIENTATION AIIALYSIS

SUMMARY

- "END ON" AND "FACE ON" CONFIGURATIONS EXHIBIT UNSTABLE FREE FLIGHT MODE CHARACTERISTICS
- "EDGE ON" CONFIGURATION WITH 50 M UTILITY TRAYS IS MOST STABLE IN UNCONTROLLED FREE FLIGHT
  - -- PEAK YAW ANGLE FOR 50 M TRAYS = 7 DEGREES; 100 METER TRAYS = 13 DEGREES
  - -- PEAK ANGULAR $\bar{H}$ FOR 50 M TRAYS = 100 NMS; 100 METER TRAYS = 50 NMS
- ALL CONFIGURATIONS REQUIRE SMALL (.09 Nm MAX) CONTROL TORQUE TO MAINTAIN ATTITUDE
  - -- MAXIMUM ANGLUAR MOMENTUM ABSORPTION REQUIRED TO MAINTAIN ATTITUDE IS 100 NMS PEAK
- REBOOST IS NEEDED WITHIN 1 YEAR FOR ALL CONFIGURATIONS
  - -- 150 KG/YR PROPELLANT @ ISP = 230 SEC REQUIRED

SAVE SPACECRAFT BUS
SYSTEM SYNTHESIS & COST ANALYSIS

A baseline model of a spacecraft utility bus was generated to use as a reference for trade off options. A description of the subsystem function requirements used to build the model is presented. This reference bus is located as shown on an earlier chart at the base of the "T" configuration.



SAVE SPACECRAFT BUS

SYSTEM SYNTHESIS & COST ANALYSIS

SYSTEM DESCRIPTION:

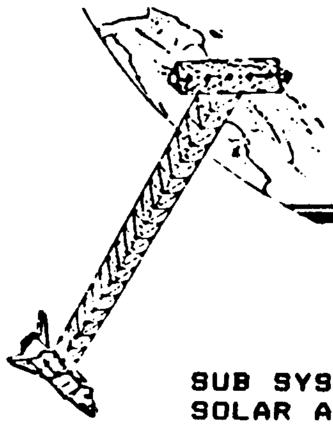
STABILITY/CONTROL:	MOMENTUM WHEEL WITH MAGNETIC TORQUER POINTING ACCURACY = 0.75 DEG COURSE / FINE SUN SENSORS & STAR TRACKER 3 AXIS INERTIAL REFERENCE UNIT
PROPULSION:	N_2 PRESSURE MMH PROPELLANT SYSTEM * TOTAL IMPULSE = 67,500 LB-SEC * DUAL 40 LB MAIN ENGINES 12 5LB RCS THRUSTERS
COMMAND & DATA:	NASA STANDARD STACC PROCESSOR UPLINK/DOWNLINK RATE = 128 KBS NUMBER OF OPERATIONAL COMMANDS = 128
COMMUNICATIONS:	S BAND TRANSPONDER @ 2200/2300 MHZ OMNI ANTENNA WITH DIPLEXER
ELECTRICAL POWER:	BODY MOUNTED SOLAR ARRAYS = 95 FT^2 SERIES LOAD REGULATION 40 AMP-HR BATTERY CAPACITY STEADY STATE LOAD = 250 WATTS
THERMAL:	PHASE CHANGE INSULATION MATERIAL 7 FT^2 BODY RADIATORS HEATER POWER @ 500 BTU/HR (INCLUDES PROPELLANT TANKS)
STRUCTURE:	9 FT. DIA X 5 FT. CYLINDRICAL SHAPE SEMI-MONOQUE ALUMINUM CONSTRUCTION (SKIN THICKNESS = 0.011 IN.)

* COMPATIBLE WITH ONCE A DAY ALTITUDE REBOOST MAINTENANCE

SAVE SPACECRAFT WEIGHT SUMMARY
(LBS)

The derived weight breakdown is shown for the spacecraft bus sized for the SAVE free flight utility bus. The total weight to be deployed from the Shuttle cargo bay would be almost 15,000 pounds.

For purposes of cost model inputs and spacecraft subsystem component redundancy considerations, one flight spane was included for each subsystem component and is assumed to be flown as a redundant unit.



SAVE SPACECRAFT WEIGHT SUMMARY (LBS)

SUB SYSTEM COMPONENTS	1,090
SOLAR ARRAY	15
INSTRUMENTATION/HARNESS	285
**STRUCTURE	489
THERMAL CONTROL	34
PAYLOAD ADAPTOR FITTINGS	51
BUS WEIGHT (DRY)	**1,964**
PROPELLANT	990
N_2 PRESSURANT	51
BUS WEIGHT (WET)	**3,005**
EXPERIMENT PAYLOAD:	
TRUSS	3,600
TIP MASS	2,000
UTILITY TRAYS	6,300
TOTAL THROW WEIGHT	**14,905**

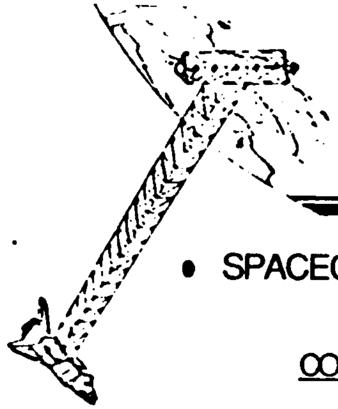
SUBSYSTEM*	LBS WT.	FT³ VOL.	WATTS PWR.
S & C	169	5.6	45.3
PROP.	150	7.9	41.0
C & D	38	0.6	8.5
COMM.	25	0.4	21.2
POWER	708	2.4	17.5

* ONE FLIGHT SPARE PRODUCED FOR EACH SPARE SUBSYSTEM COMPONENT. EACH FLIGHT SPARE FLOWN AS IN-FLIGHT REDUNDANT UNIT.

** ORBITER TRUNION AND KEEL ADAPTERS INCLUDED FOR S\C BUS ONLY

SAVE SPACECRAFT BUS
SYSTEM SYNTHESIS & COST ANALYSIS

A baselined model of a spacecraft utility bus was generated to use as a reference for trade off options. A description of the subsystem function requirements used to build the model is presented. This reference bus is located as shown on an earlier chart at the base of the "T" configuration.



SAVE SPACECRAFT COST SUMMARY ($K)

- SPACECRAFT BUS

COST ELEMENT	(NON-RECURRING) DDT&E	COST ELEMENT	(RECURRING) INVESTMENT
DESIGN ENGINEERING	7,258	PRODUCTION ENGINEERING	783
DEVELOPMENT TESTING	5,310	PRODUCTION	6,856
TOOLING & TEST EQUIP	631	TOOLING & TEST EQUIP	823
QUALITY ASSURANCE	835	QUALITY ASSURANCE	1,079
SE & I	3,926		
PROGRAM MANAGEMENT	2,337		
TOTALS	20,297		9,541

- PROGRAM COST

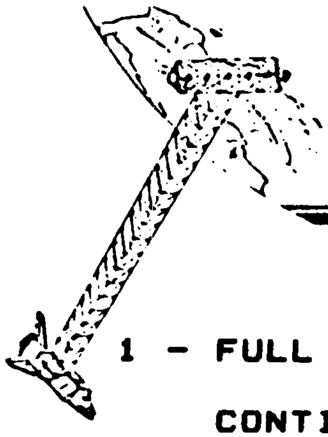
COST ELEMENT	DDT &E	INVESTMENT	OPERATIONS
SPACECRAFT	20,297	9,541	
CONTRACTOR FEE @ 8%	1,624	1,763	
AGE (GFE)	1,652		
LAUNCH INTEGRATION/OPS			4,116
FLIGHT OPERATIONS			3,000
PROGRAM TOTALS	23,546	10,304	7,116

SAVE SPACECRAFT TOTAL = $41M

SAVE SPACECRAFT BUS OPTIONS

Three other spacecraft bus options were generated to trade-off various options of free flight attitude control and orbit reboost thrust vector control. Option 2 utilizes the instrumentation sensors used for the structure dynamic testing performed while attached to the Shuttle orbiter. They are integrated with the other elements of the spacecraft flight control system to sense vehicle rotation motion and acceleration. Option 2 is passively stabilized between reboost maneuvers and requires a pitch maneuver to align the z axis along the thrust vector for an orbit reboost. Option 3 locates separate reboost utility packages on each end of the z-axis such that the vehicle does not need to be pitched over to an "end on" reboost attitude, but can remain in a "face on" or "edge on" Local Vertical/Local Horizontal (LV/LH) attitude which never changes for orbit reboost. Option 4 is passively stabilized but uses low continuous thrust engines to maintain altitude in a split bus configuration.

Trade-off analyses of these options were performed and are presented in Section I of this report.



SAVE SPACECRAFT BUS OPTIONS

OPTION	COST
1 - FULL UP ACTIVE BUS	41 $M
CONTINIOUS OPERATION / STABILITY & CONTROL ACTIVE FLIGHT OPERATIONS	
2 - INTEGRATED SENSOR / ACTIVE REBOOST	31 $M
EXPERIMENT ACCELEROMETERS & GYROS UTILIZED PASSIVE STABILIZATION BETWEEN REBOOST MANUEVERS 3 AXIS ACTIVE REBOOST THRUST VECTOR CONTROL FLIGHT TEAM REBOOST SUPPORT	
3 - SPLIT-BUSS ACTIVE REBOOST CONTROL	26 $M
SEPARATED REBOOST ENGINES LOCATED ON TRUSS MINIMIZES ATTITUDE MANUEVER RESOURCES REQUIRES EXTRA EVA ASSEMBLY TIME ACTIVE REBOOST THRUST CONTROL / INTEGRATED SENSORS FLIGHT TEAM REBOOST SUPPORT	
4 - FULLY PASSIVE STABILIZATION & REBOOST CONTROL	15 $M
SPLIT BUSS / INTEGRATED SENSORS LOW CONTINUOUS THRUST ION ENGINES ACCEPT DELTA V THRUST VECTOR LOSSES NO ACTIVE FLIGHT TEAM SUPPORT MINIMUM COMMUNICATIONS, COMMAND & DATA	

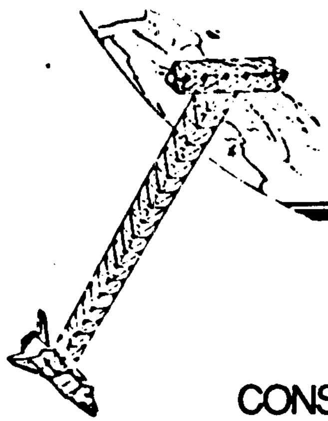
80 METER TRUSS CONFIGURATION ANALYSIS

However, before spacecraft bus trade-offs could be made certain analysis needed to be performed to provide parametric information to consider for minimizing spacecraft bus requirements.

Studies of assembly timelines indicated that EVA timelines could be minimized if the SAVE configuration could be left on a "face on" flight orientation. This required investigation into momentum wheel sizing for providing a passive yaw stabilization approach to eliminate full time active control between reboost maneuvers.

A reboost Delta V manuever strategy needed to be baselined to evaluate a 270-220 nautical mile attitude maintenance approach versus a continous low thrust drag make-up approach. The control requirements to assess sizing trades for attitude control maneuvers from "face on" to "end on" orientation to perform orbit reboost versus split bus pitch/yaw sensitivity to Delta V thrust misalignment was investigated.

These studies were performed using a 16 x 5 bay truss configuration as shown in the following 3 pages. The number of z-axis truss bays was reduced from 20 to 16 at this point in the study to minimize EVA timeline requirements.



80 METER TRUSS CONFIGURATION ANALYSIS

CONSIDERATIONS FOR MINIMIZING S/C BUS REQUIREMENTS:

1 - ASSESS FACE ON FLIGHT ORIENTATION REQUIREMENTS/CHARACTERISTICS

- MINIMIZES ASSEMBLY EVA TIME

2 - MOMENTUM WHEEL SIZING FOR PASSIVE YAW STABILIZATION

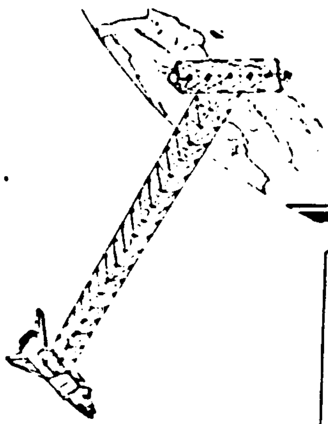
- ELIMINATE FULL TIME ACTIVE CONTROL BETWEEN REBOOST MANEUVERS

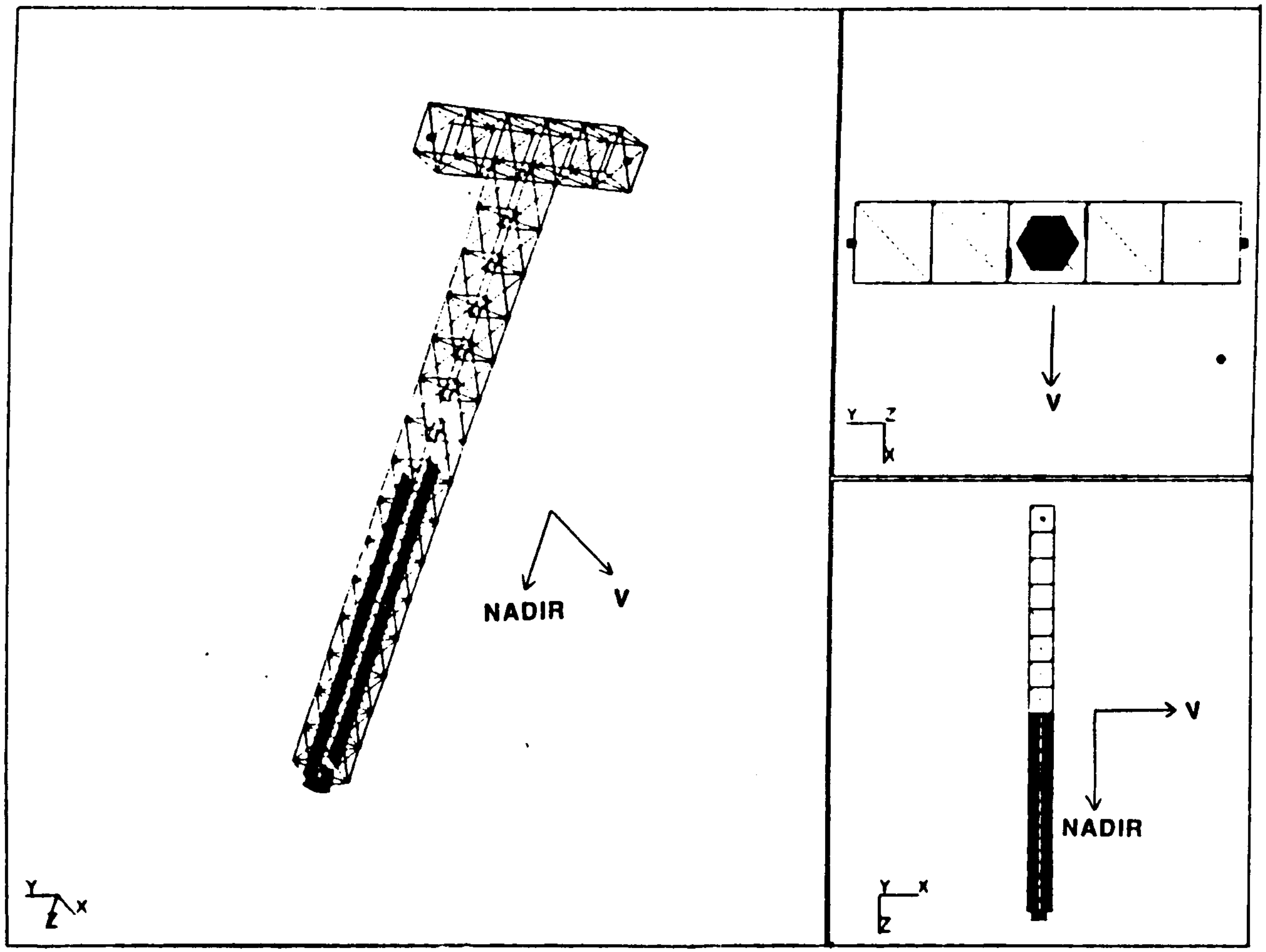
3 - REBOOST DELTA V MANEUVER ANALYSIS

- PROPELLANT REQUIREMENT DETERMINATION FOR 270-220 NMI ALTITUDE MAINTENANCE VERSUS CONTINUOUS LOW THRUST DRAG MAKE-UP
- REBOOST ATTITUDE MANEUVER CONTROL SIZING FROM FACE ON TO END ON ORIENTATION
- PITCH/YAW SENSITIVITY TO DELTA V THRUSTER MISALIGNMENT

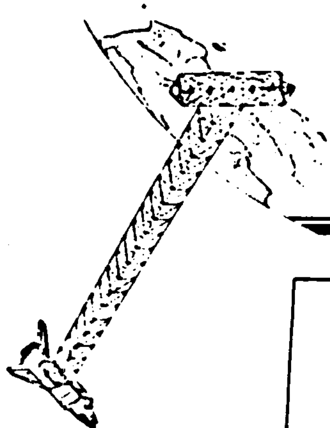
16 BAY (80 METER) FACE ON GEOMETRY

16 X 5 BAY FACE ON

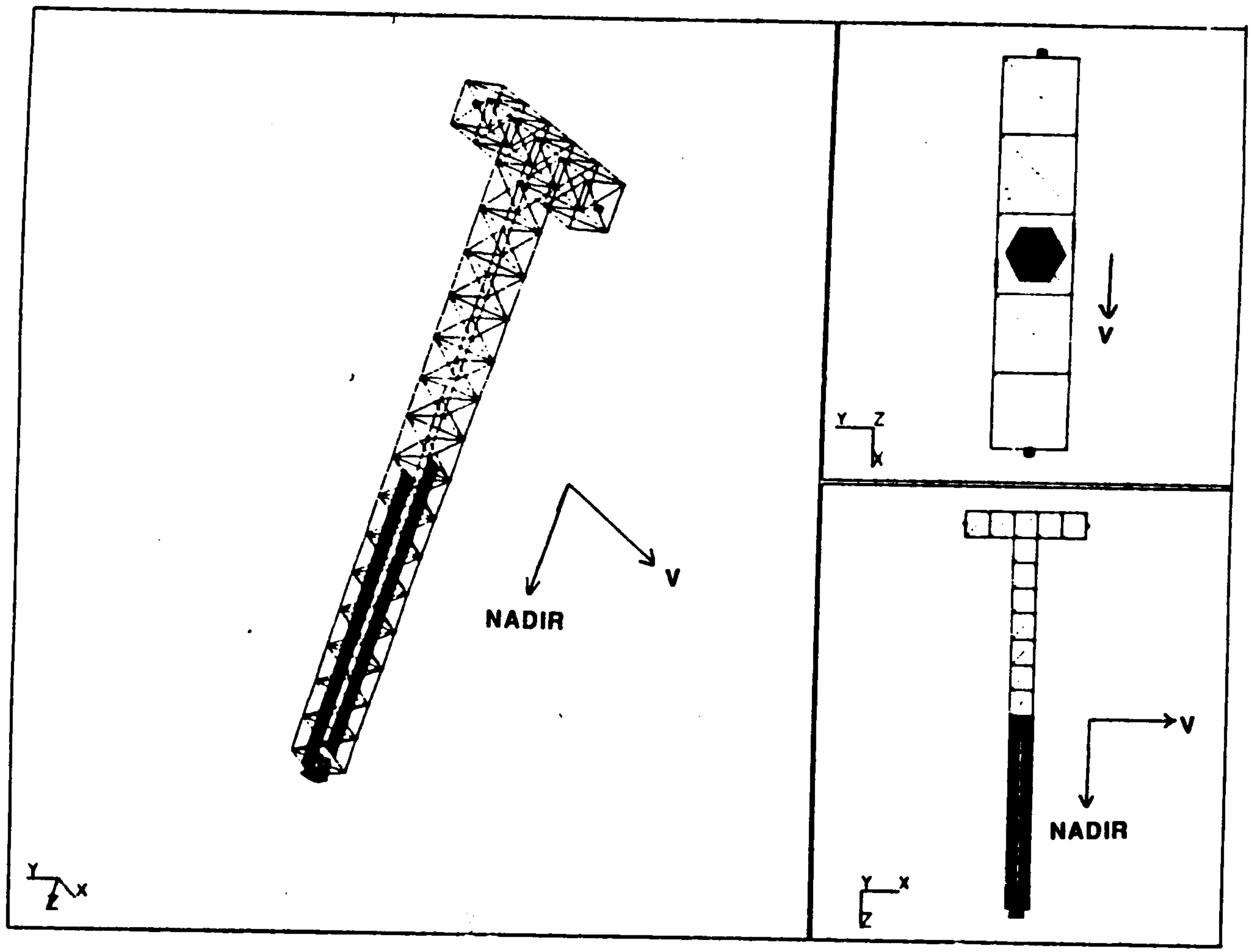




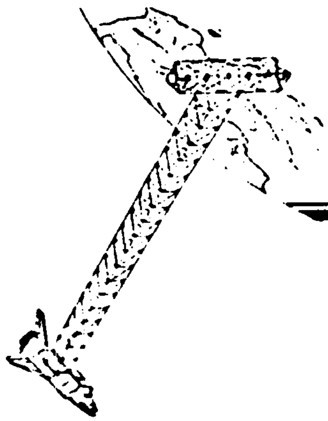
16 BAY (80 METER) EDGE ON GEOMETRY



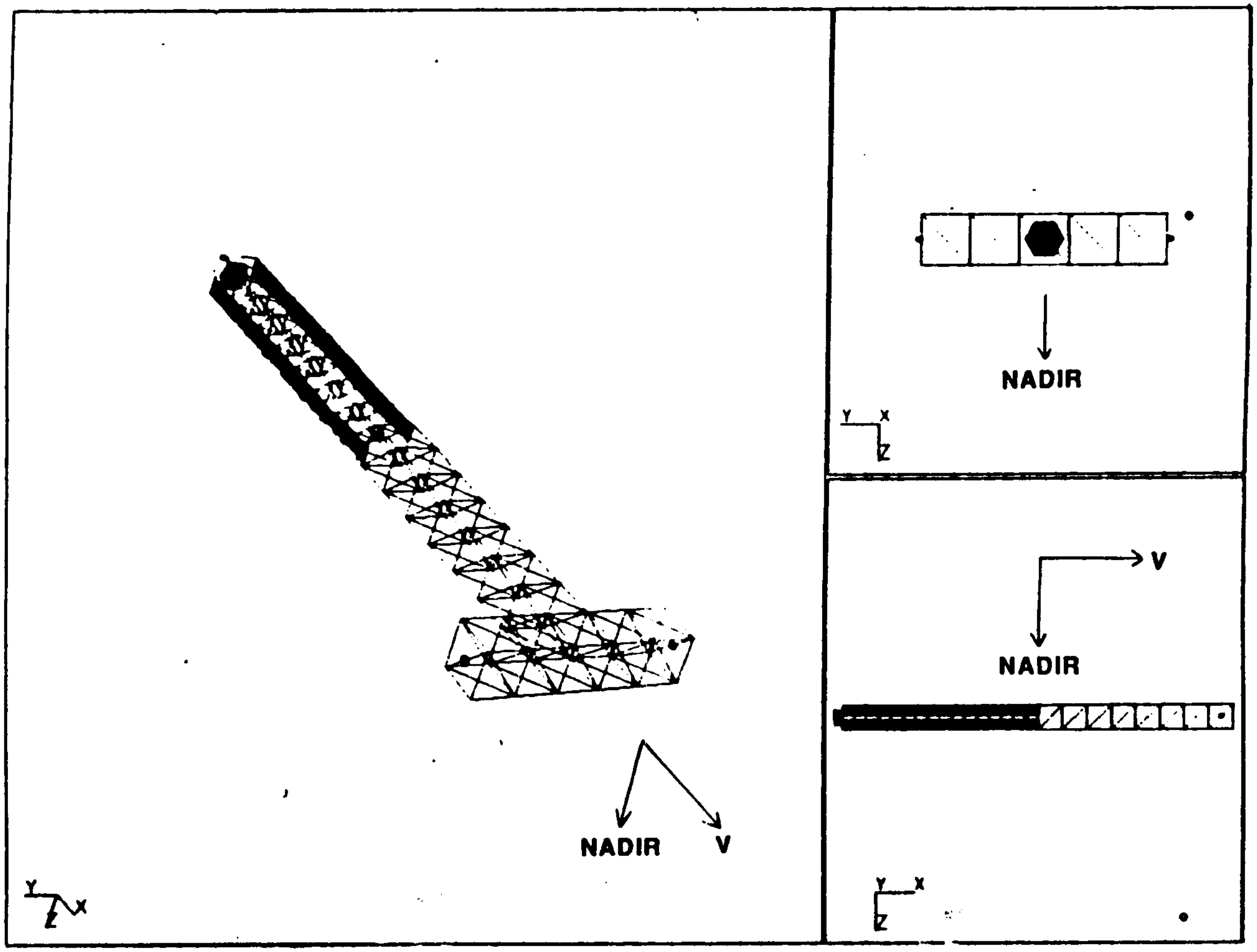
16 X 5 BAY EDGE ON



16 BAY (80 METER) END ON GEOMETRY

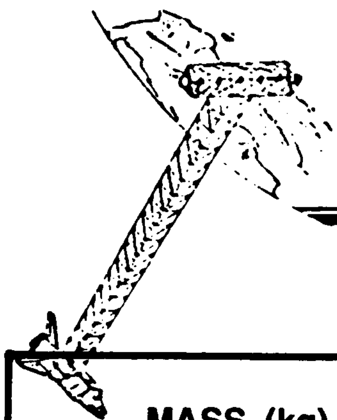


16 X 5 BAY END ON



PHYSICAL CHARACTERISTICS

Physical characteristics for the 16 x 5 bay revised SAVE configuration were derived. Inertia characteristics basically remain similar to the 20 bay configuration. Minor reductions in weight and aerodynamic drag can be noted.



PHYSICAL CHARACTERISTICS

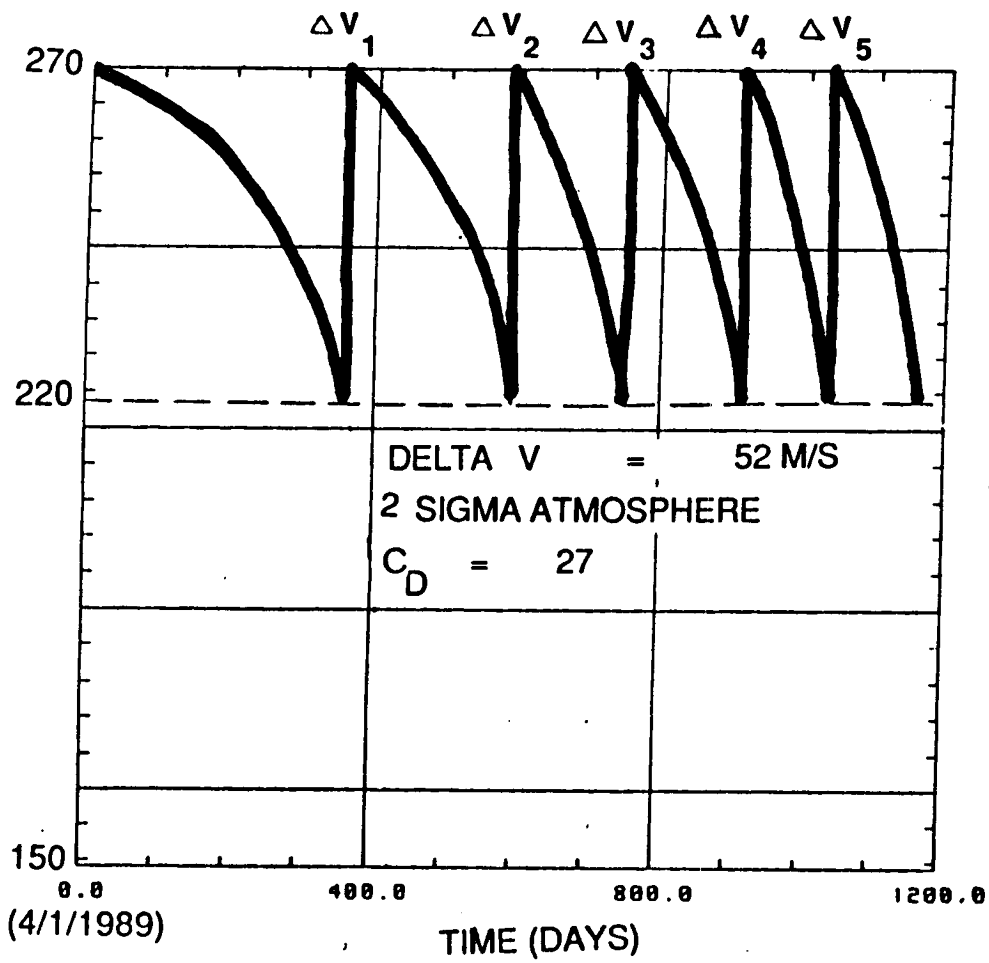
	FACE ON	EDGE ON	END ON
MASS (kg)	5834	5834	5834
DRAG AREA (m^2)	93	93	89
INERTIA ($KG\ M^2$)			
I_{XX}	5.31 E6	5.14 E6	1.97 E5
I_{YY}	5.13 E6	5.30 E6	5.30 E6
I_{ZZ}	1.97 E5	1.97 E5	5.14 E6
I_{XY}	7.14 E3	7.14 E3	0
I_{XZ}	0	0	0
I_{YZ}	0	0	7.14 E3

FACE ON ORBIT DECAY AND DISCRETE REBOOST

The aerodynamic drag areas for the 16 x 5 bay SAVE configuration of 93 meters for the stable LV/LH vehicle orientation still requires the first orbit reboost maneuver to be performed in about one year from initial deployment at 270 nautical miles. Using a 2 burn Hohmann transfer analysis (first Delta V maneuver to raise the altitude from 220 nautical miles and the second Delta V maneuver to circularize the orbit) the reboost profile shown was determined. The increasing frequency of reboost maneuvers is due to the overall spacecraft weight being depleted from propellant useage and the increasing yearly atmospheric density.

A fuel requirement of 760 Kilograms (1700 lbs) for a 3 year mission lifetime is required using this strategy for the "face on" or "edge on" LV/LH flight mode orientation.

FACE ON ORBIT DECAY AND DISCRETE REBOOST



M_{F1} = 132 kg

M_{F2} = 129 kg

M_{F3} = 126 Kg

M_{F4} = 124 kg

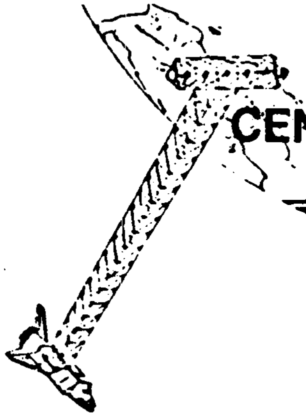
M_{F5} = 121 kg

632 kg
+ 20 %

M_{Fuel} =760 kg

CENTER OF GRAVITY - CENTER OF PRESSURE OFFSETS

For vehicle maneuver orientation studies the center of gravity offsets from the center of aerodynamic pressure were calculated in all three of the yz, xz, and xy planes. CG-CP offsets of 11.3 meters in the respective planes are shown which provide the moment arms for aerodynamic forces to impact torques which the SAVE spacecraft control system must be sized to counteract.

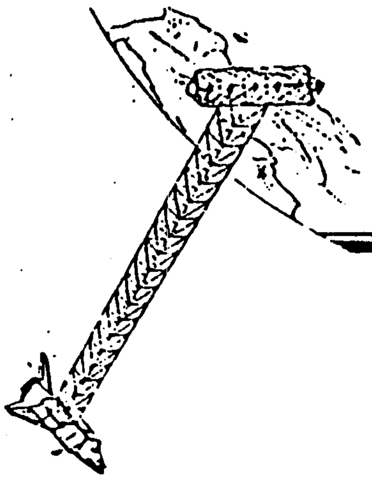


CENTER OF GRAVITY - CENTER OF PRESSURE OFFSETS

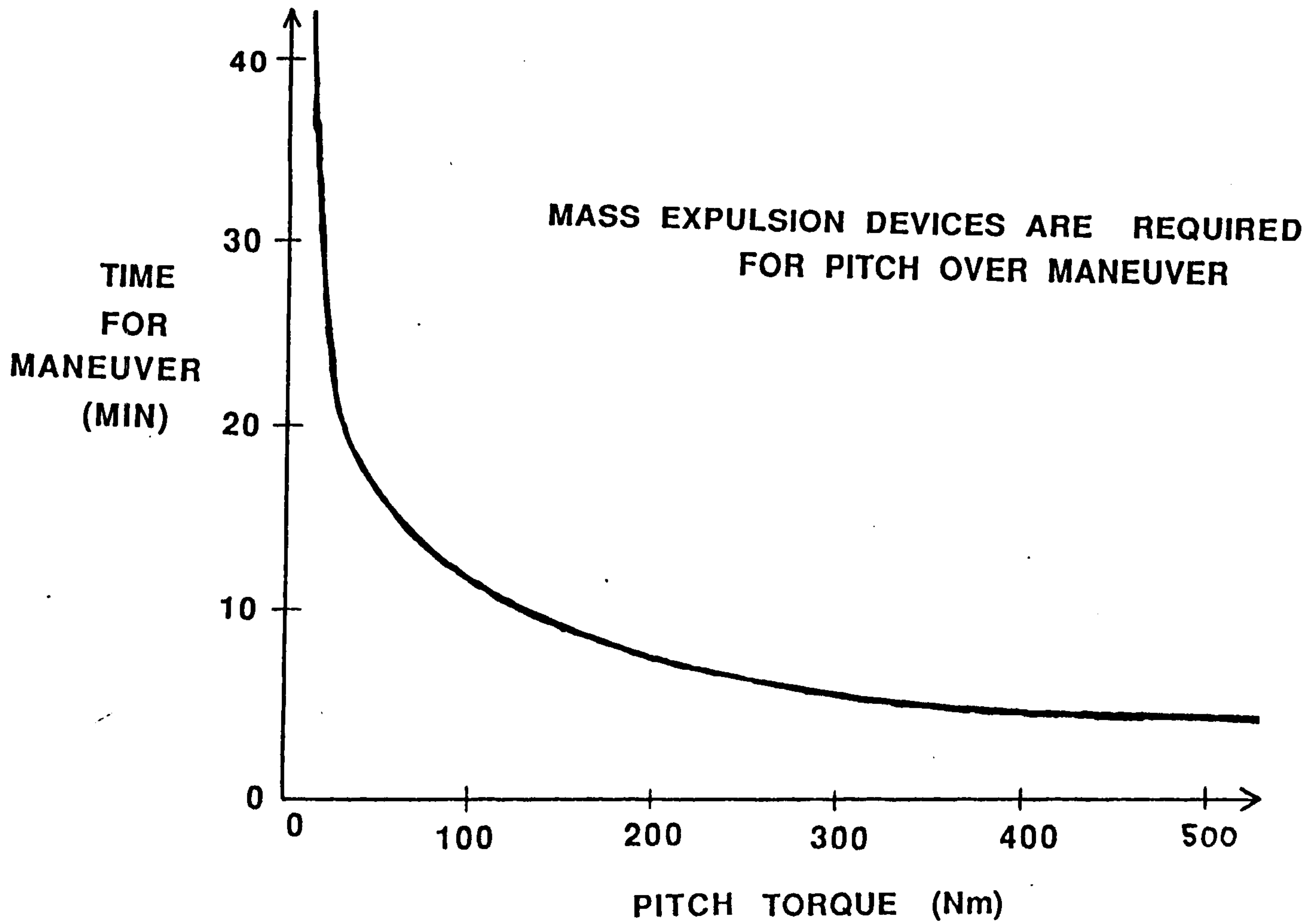
	Cg - Cpx (meters)		Cg - Cpy (meters)		Cg - Cpz (meters)	
	Y	Z	X	Z	X	Y
FACE ON	O	-11.3	O	1.2	O	O
EDGE ON	O	-11.3	O	1.2	O	O
END ON	O	O	-1.2	O	11.3	O

PITCH OVER MANEUVER FROM FACE ON TO END ON

To perform a reboost maneuver to align the thrust vector through the center of gravity and along the z axis (for engines located at the bottom of the 16 meter truss thrusting in the +z direction) a pitch over maneuver must be performed. The torque/time profile for this maneuver for the vehicle inertias and environmental torques encountered is shown. For the torques required to start and stop this maneuver, mass expulsion reaction control devices are the most likely candidates.

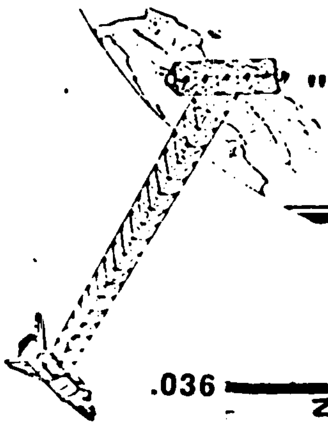


PITCH OVER MANEUVER FROM FACE ON TO END ON

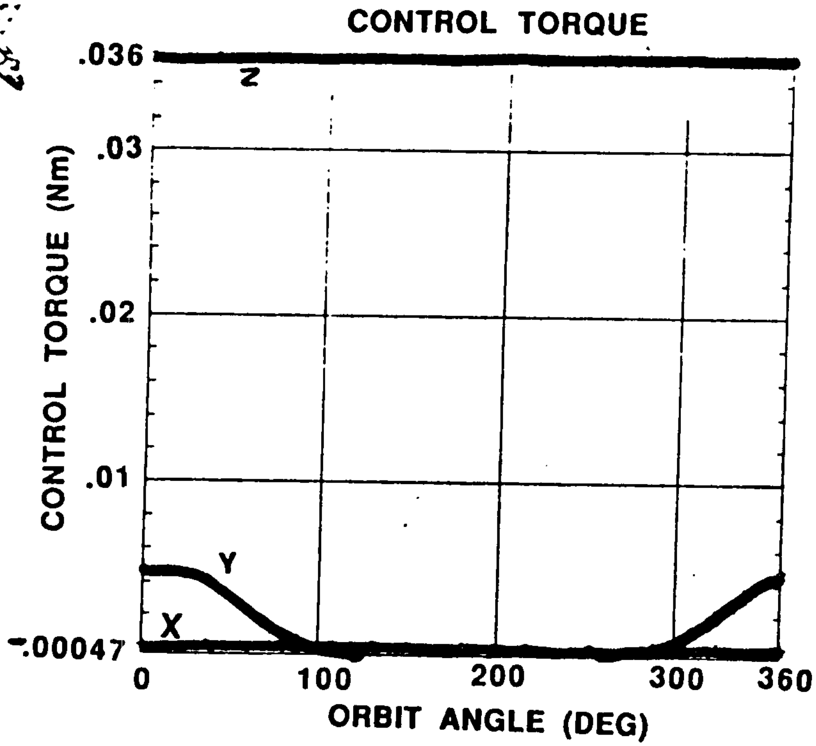


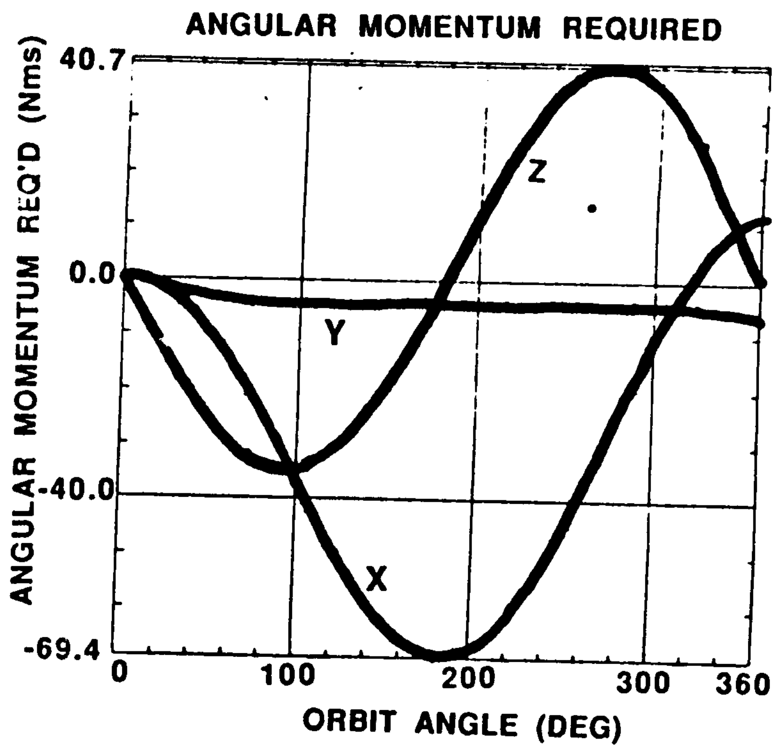
"END ON" FLIGHT MODE REQUIRES ACTIVE CONTROL TO MAINTAIN ATTITUDE

After achieving an "end on" orientation for reboost Delta V position, active control must be employed to maintain this attitude. As has been shown the "T" truss configuration will tumble if left uncontrolled in this attitude. Shown here are the time varying control torque and angular momentum absorption requirements required to maintain this attitude orientation.



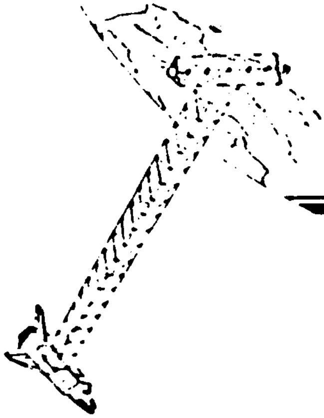
"END ON" FLIGHT MODE REQUIRES ACTIVE CONTROL TO MAINTAIN ATTITUDE





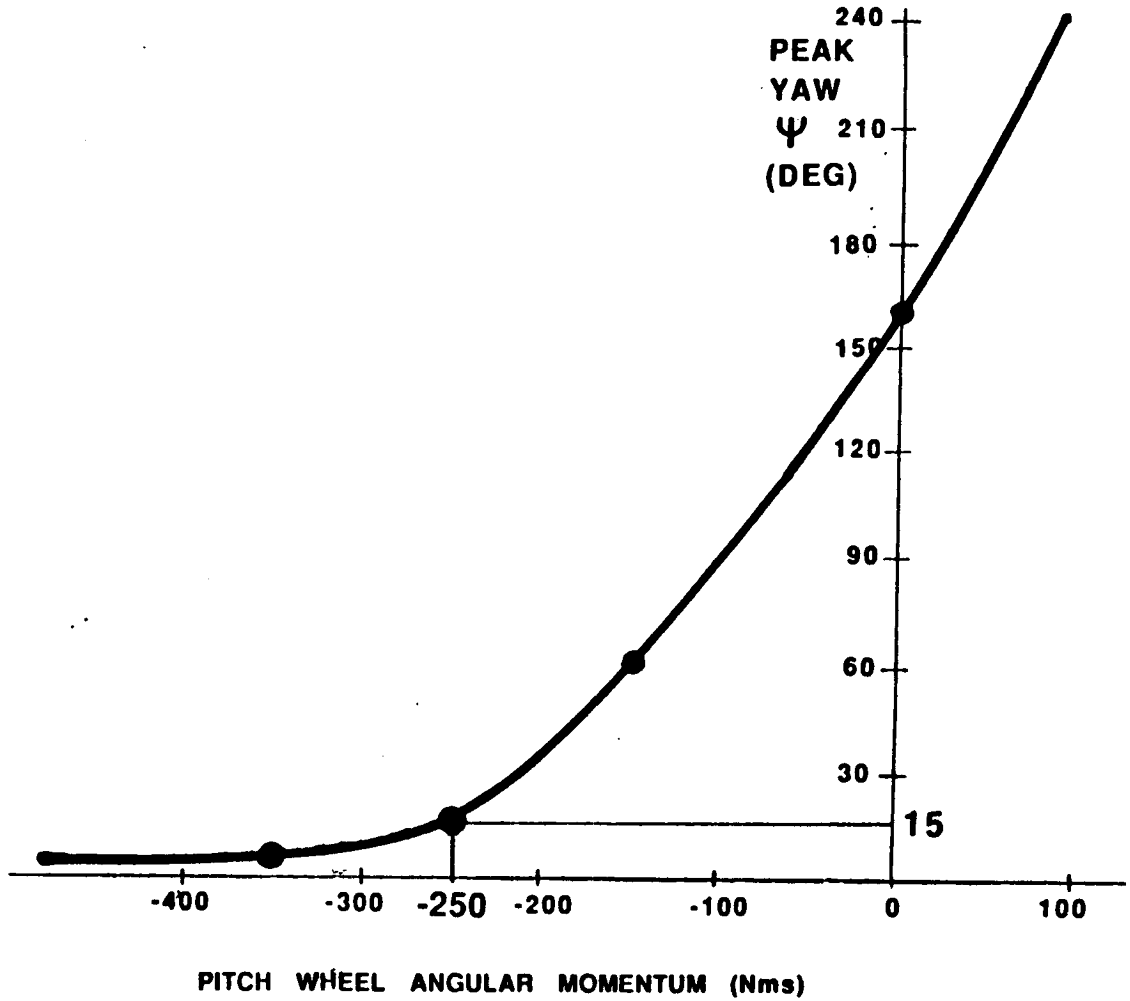
FIXED PITCH MOMENTUM WHEEL SIZING

The "face on" attitude orientation exhibits uncontrolled yaw channel attitude position errors of up to about 160 degrees. To stabilize this motion with a fixed pitch axis momentum wheel, the curve shown was determined for the SAVE 16 x 5 truss configuration in the "face on" LV/LH flight mode. The uncontrolled data point of 160 degrees is shown for no applied angular momentum absorption for active control. If a 250 Newton meter second momentum wheel is selected it will reduce the peak yaw motion to 15 degrees as shown.



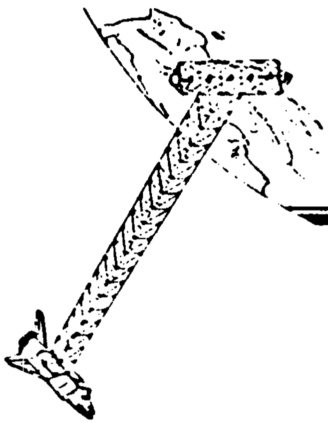
FIXED PITCH MOMENTUM WHEEL SIZING

FACE ON RESPONSE DUE TO ENVIRONMENTAL TORQUES



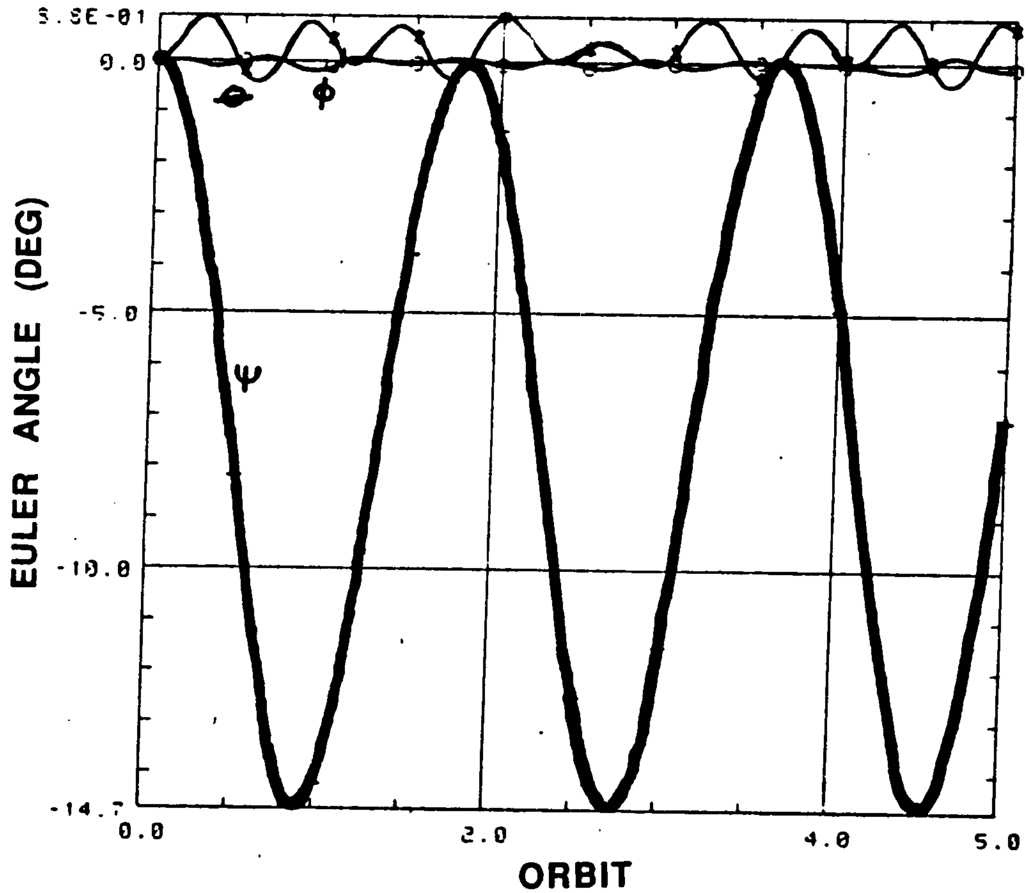
FACE ON WITH - 250 NMS WHEEL

The yaw channel response of the SAVE 16 x 5 truss with dual 50 meter long utility trays and a 3000 pound spacecraft bus attached is shown. The peak cyclic yaw channel response is 14.7 degrees over a 5 orbit observation period.



FACE ON WITH - 250 N ms WHEEL

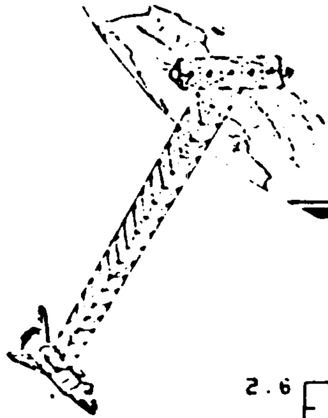
VEHICLE ATTITUDE



CONTINUOUS REBOOST

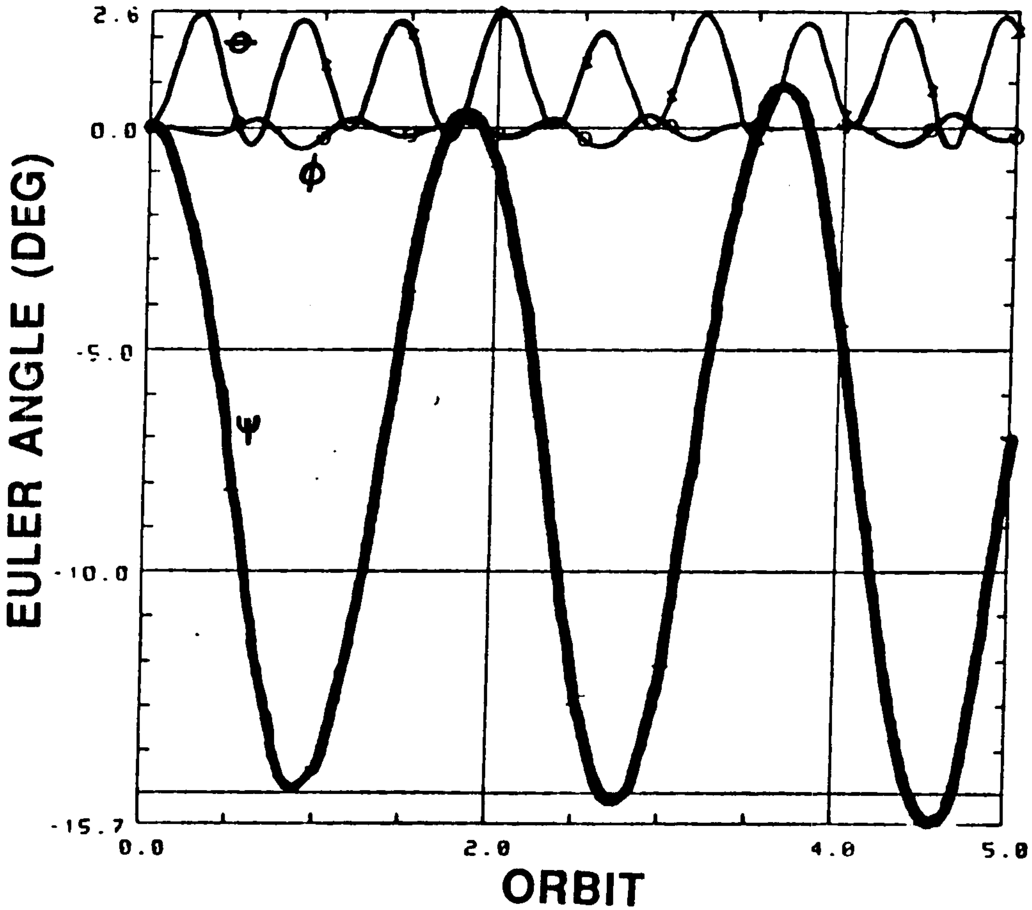
Considering a continouus reboost for a single continuous low thrust level of 0.002 pound force in the direction shown, thruster misalignment of -15.7 degrees in the yaw channel is predicted with a 250 Newton-meter-second pitch momentum wheel. The pitch channel response of up to 2.6 degrees is shown for the five orbit observation period.

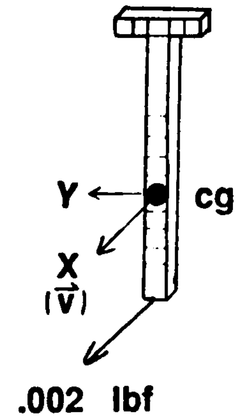
This reboost strategy would eliminate the need for a pitch over maneuver for reboost. However, the propellant useage must be scaled up to handle the thruster misalignment errors if this strategy is to be considered.



CONTINUOUS REBOOST

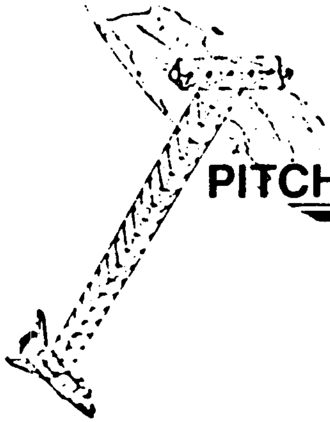
FACE ON WITH -250 Nms WHEEL
VEHICLE ATTITUDE



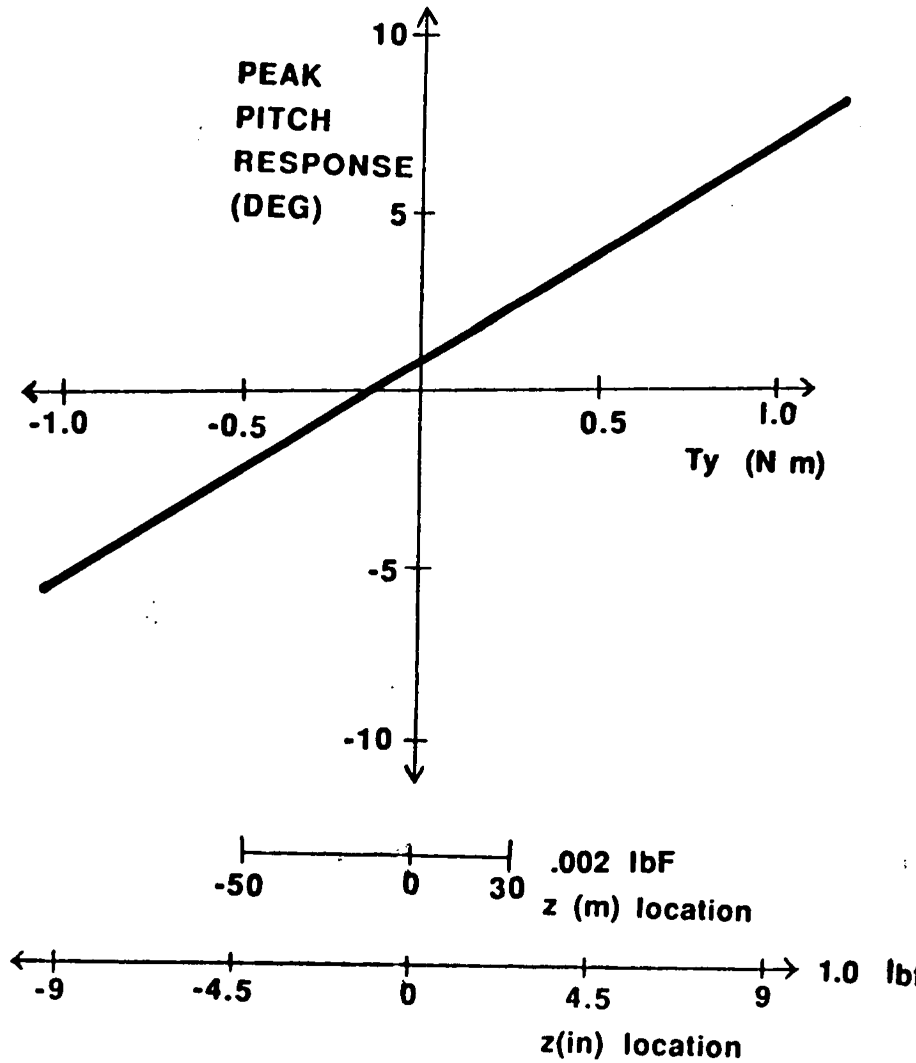


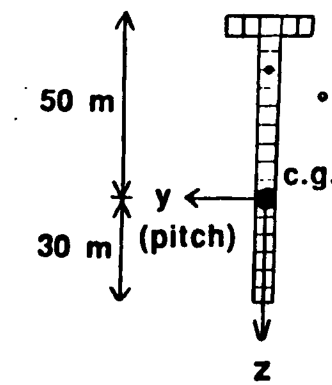
PITCH SENSITIVITY DUE TO CONTINUOUS THRUST MISALIGNMENT

When oriented on the LV/LH attitude, if the vehicle is subjected to a continuous thrust to maintain altitude which is misaligned from the vehicle c.g., then a continuous torque is exerted on the vehicle. The following figure illustrates the pitch response sensitivity to a steady pitching torque. Since the vehicle is gravity gradient stable in pitch, it is relatively insensitive to a pitching torque. A continuous 0.002 lbf thrust can be located anywhere along the z axis on SAVE without causing a peak pitch response of more than 3 degrees. A 1.0 lbf thrust can be located within 9 inches along the z axis from the c.g. without causing a peak pitch response of more than 5 degrees.



PITCH SENSITIVITY DUE TO CONTINUOUS THRUST MISALIGMENT

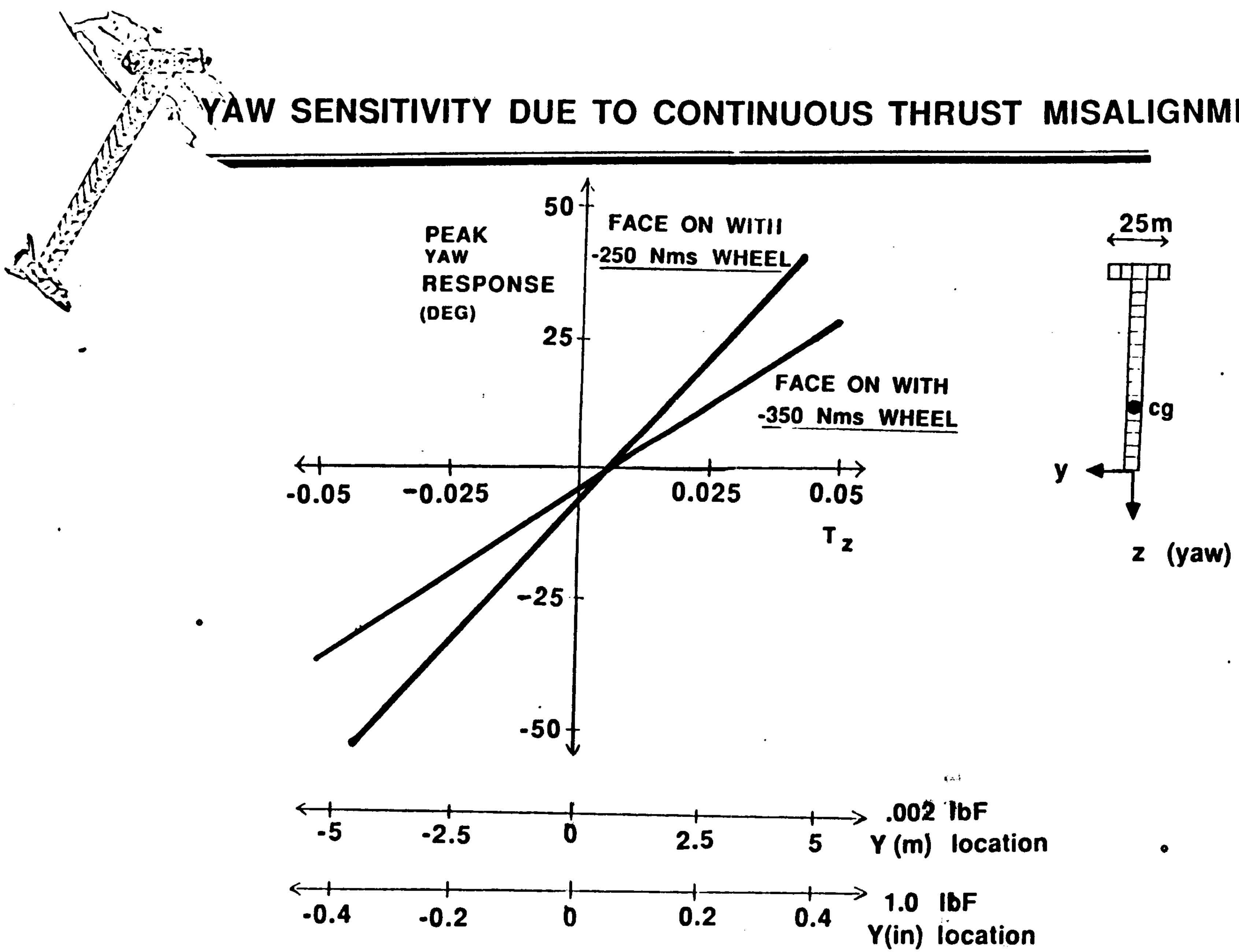




YAW SENSITIVITY DUE TO CONTINUOUS THRUST MISALIGNMENT

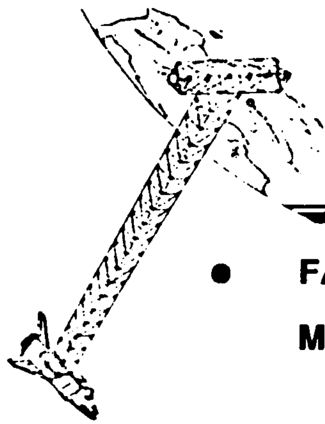
Although the SAVE 16 x 5 configuration is relatively insensitive in pitch response to a thrust misalignment, it is very sensitive in yaw response to a yaw torque caused by a thrust misalignment. For the "face on" configuration with a 250 Nms pitch wheel, the peak yaw response will reach 20 degrees if a 1 lbf thrust is located 0.2 inches in the y direction from the c.g. For the same configuration with a 350 Nms wheel, the peak yaw response will reach 15 degrees.

YAW SENSITIVITY DUE TO CONTINUOUS THRUST MISALIGNMENT



SUMMARY

The chart shown summarizes the major points of consideration for the assessments made to minimize the SAVE spacecraft bus requirements. The considerations will be applied to assessments made of the derived spacecraft bus configuration options to be presented in Section I of this report.



SUMMARY

- FACE ON FLIGHT ORIENTATION REQUIRES FIXED PITCH MOMENTUM WHEEL FOR PASSIVE YAW STABILIZATION
  - PITCH WHEEL = -250 Nms LIMITS PEAK YAW TO 15 DEG
  - PITCH WHEEL = -350 Nms LIMITS PEAK YAW TO 6 DEG
  - PITCH WHEEL = -1200 Nms LIMITS PEAK YAW TO 1 DEG
- ACTIVE CONTROL REQUIRED FOR END ON REBOOST ΔV MANEUVER
  - 400 Nm TORQUE REQUIRED FOR PITCH OVER MANEUVER @ 0.3 DEG/SEC MANEUVER RATE
  - 0.04 Nm PEAK CONTROL TORQUE REQUIRED TO MAINTAIN END ON ATTITUDE
- THREE YEAR LIFETIME REQUIRES FIVE DISCRETE REBOOSTS FROM 220 NM TO 270 NM OR CONTINUOUS REBOOST
  - DISCRETE REBOOST TOTAL FUEL = 760 KG
  - CONTINUOUS REBOOST THRUST = .002 lbF
- LOW THRUST RECOMMENDED TO DIMINISH YAW MOTION SENSITIVITY DUE TO THRUSTER MISALIGNMENT

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16. Abstract

A design concept for a 5 M erectable space station STS structures flight experiment is developed and discussed. The main considerations examined in developing the design concept are (1) space station structural configuration, (2) space station structural assembly procedures, timelines and operations, and (3) on-orbit space station structural dynamic testing. The concept is developed using current hardware design concepts, maximizing use of the shuttle Remote Manipulation System (RMS) and simulating space station extravehicular activity (EVA) procedures. In addition to the experiment hardware description, analysis, and results, this report describes the resources required to perform this STS experiment. The report also indicates the spacecraft bus requirements necessary for a free flyer three-year lifetime capability.

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